Interpreting a Weird and Scenic Landscape to Park Visitors: Tectonic and Volcanic Processes of Craters of the Moon National Monument and Preserve, Idaho

by
Kimberly E. Truitt and Robert J. Lillie
Oregon State University

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Kimberly E. Truitt
Robert J. Lillie

Department of Geosciences
Oregon State University
Corvallis, Oregon 97331

ketruitt@gmail.com
lillier@geo.oregonstate.edu

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PREFACE

by Kim Truitt

For two seasons, I had the pleasure of sharing the beauty of the lava flows, cinder cones, lava tube caves, and other wonders of Craters of the Moon National Monument and Preserve (CRMO) to park visitors who were curious and excited about this strange place. For many, it reminded them of the volcanoes and lava flows of Hawai'i. Many were also visiting Yellowstone National Park (YNP) and were eager to learn about the connections between these two seemingly contrasting landscapes. Whether explaining the exhibits to be found in the park's Visitor Center, or out hiking with visitors among the cinder cones and lava flows, my excitement and appreciation for this unique volcanic landscape never waned.

This manual presents geology in a such a way that rangers can present it to audiences not familiar with the subject. The wonders of CRMO are due to geologic processes that will continue to modify the landscape for centuries to come. It is hoped that Park Rangers and educators without extensive geology backgrounds will be able to use each of the chapters as starting points for their programs or lessons on the basic geologic processes of CRMO. Those more familiar with geology should also be able to use the "In Depth" sections to further investigate aspects of CRMO's geology that they are curious about or that visitors want to investigate during their visits.

The Six Principles of Interpretation, from Freeman Tilden's *Interpreting Our Heritage* (1977), are presented as a basis for preparing interpretive programs. Interspersed throughout, these six principles are presented along with interpretive techniques I found useful for programs at CRMO or with subjects of interest to visitors that present additional interpretive opportunities for park staff and educators. Potential geological themes that may be used for interpretive programs presented at CRMO are also included.

To help translate the mysteries of how this strange landscape formed, I've found that it can be helpful to compare the volcanic features of CRMO to

The Spatter Cones are one of the most popular features of the CRMO landscape. The story of their formation presents many interpretive opportunities for Park Rangers to engage the visiting public on the wonders of this vast volcanic landscape (Photograph by R.J. Lillie).

recent volcanic activity that visitors may be more familiar with in Hawai'i or Iceland. Seeing a picture of lava erupting out of a spatter cone or of a lava fountain above a growing cinder cone can be a great way to show people what happened at CRMO a few thousand years ago, and may happen again within our lifetimes or the centuries to follow.

Most visitors to CRMO are fascinated with Yellowstone National Park and its many hydrothermal features. Much attention has been paid to the geologic connections between the Yellowstone Hotspot and volcanic activity at CRMO.

Other topics of importance to CRMO's geology are also presented, especially continental extension of the Basin and Range Province. This extension is partly responsible for the volcanic features of CRMO, not to mention the earthquake activity in the Lost River Range and other nearby mountains. Many local residents remember the 1983 Borah Peak earthquake and how it affected their lives. Visitors can see the visual scarring of the local landscape from this recent major earthquake along the Lost River Range.

It is my hope that park naturalists and teachers will be able to use this manual as a reference in preparing interpretive programs at CRMO, or in classrooms as a guide to the geologic features that students can learn about and explore while visiting CRMO. This unique volcanic landscape is one of Idaho's, and America's, not-so-well known gems. One day, more volcanic eruptions might occur and the landscape will change and evolve again as it has been doing regularly for the past 15,000 years. As more is known about the ongoing geologic processes of CRMO, by both scientists and the visiting public, we can all grow in our understanding and appreciation of this beautiful landscape.

The purpose of this manual is to help the interpretive staff convey geologic principles to park visitors experiencing a landscape formed by volcanic processes. Basic geology and the most current research on local and regional levels are incorporated in ways that are understandable to the staff and meaningful to park visitors. Interpretive staff will be encouraged to include more geological concepts into their own interpretive programs than they might otherwise.

The first chapter introduces the reader to the interpretive methods and materials currently being used by CRMO staff and offers additional interpretive themes that may be utilized in presenting the geology of CRMO to the visiting public. The second chapter presents concepts of geology that are universal to interpretation at National Park Service sites involving volcanic features and processes. It includes basic explanations of plate tectonics and volcanism, emphasizing basaltic magmas and their eruptive products. The third chapter gives a broad geological perspective of the CRMO area by emphasizing ongoing hotspot and continental rifting processes. This includes an overview of the Yellowstone Plateau, the eastern Snake River Plain (ESRP), and the northern Basin and Range Province. It also provides a perspective on CRMO's spatial and temporal relationships to these provinces. The overview explains the decompression melting responsible for volcanism associated with hotspots and continental rift zones. With this background information, the fourth chapter presents the geology of the Great Rift Zone and the Craters of the Moon (COM) lava field and its development through a sequence of lava flows during the past 15,000 years. This leads to discussions of the many volcanic features found within the COM lava field, such as craters and cinder cones and the types of lava flows.

Chapter 4 also presents research and geological mapping of the eruptive and non-eruptive fissures present in the CRMO Wilderness. Presentation of this research will aid geological interpretation at CRMO by giving the interpretive staff a clearer picture of the similarity of Basin and Range extension to the patterns of ongoing rifting and volcanism at CRMO.

For each chapter, the beginning is non-technical and written for a non-geologist audience. Following the introductory material is technical information written for a geologist audience which focuses on recent research being performed on the geology of the CRMO area. Topics devoted to geological interpretation methods are also included in each chapter.

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ACKNOWLEDGEMENTS

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We are thankful to both Craters of the Moon National Monument and Preserve and the Bureau of Land Management for their support of Kim during her two seasons as an Interpretive Ranger at the park. The Interpretive Ranger position was financially supported by the Bureau of Land Management, the agency that jointly manages CRMO with the National Park Service. Craters of the Moon National Monument and Preserve provided logistical support, training, encouragement, and a wealth of other means of assistance to Kim. Comments and reviews by Douglass Owen, Ted Stout, Mel Kuntz, Scott Hughes, Lennie Ramacher, and Tiffany Rivera were especially helpful in the preparation of the thesis and manual.

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Dedicated to Margaret W. Truitt.
You would have loved the desert in bloom ....

CHAPTER 1

Geology Interpretation at Craters of the Moon National Monument and Preserve

The focus of geology interpretation at Craters of the Moon National Monument and Preserve (CRMO) is the Great Rift volcanic rift zone (Great Rift) and its associated lava flows. The monument showcases some of the youngest and most extensive examples of crustal extension and associated volcanism in the United States. CRMO's location among the lava flows of a volcanic rift zone make it a natural geology classroom. Many outstanding volcanic features, such as pāhoehoe and ´a´ā lava flows, cinder and spatter cones, lava tubes, pressure ridges, lava bombs, eruptive and non-eruptive fissures, and pit craters are easily accessible to park visitors via hiking trails accessible by an automobile loop (Loop Road). Daily ranger-led hikes are given along the Broken Top Loop and the Caves Trail during the summer season. Weekly evening programs highlight the many natural and historical aspects of the park, including geology, that intrigue visitors.

According to the CRMO's *Visitor Study for Summer 2004*, the majority of visitors were between 45 and 65, or were younger than 15. Most were visiting CRMO with their family. These visitors were dominantly from California, Idaho, and Washington. Those from foreign countries visited mostly from Canada, Germany, and Holland. The majority of visitors (72%) came for general sightseeing. A smaller percentage of them were interested in the geological features (9%). Results from the study highlight the importance of interpretive materials that present the geology of CRMO in ways that are understandable and meaningful for an audience not familiar with geology.

An array of research and educational materials focused on CRMO geology has been developed in the last few years. "Geology of Craters of the Moon," written by CRMO Interpretive Ranger and Park Geologist Douglass Owen, overviews the geology of CRMO's lava flows and many volcanic features and is available to interpretive staff, educators, and the general public via the Internet (Owen, 2003). An educational unit, "Teacher's Guide to Broken Top Loop," discusses the geological and biological features present in the area surrounding the Broken Top cinder cone (Owen, 2004). An examination of the development of North Crater and the areas of rafted blocks that originated from this cinder cone, "The North Crater Neighborhood: More Complex Than Mister Rogers' – A discussion of cinder cones, lava flows, and rafted blocks," has been developed by BLM Geology Technician Cooper Brossy (Brossy, 2003). In 2005, NPS Geoscientist-in-the-Parks (GIP) volunteers Rachel Clennon and Kathryn Wetherell completed a detailed map of the many geologic features in the Broken Top area. An expanded interpretation of the mechanisms of the eruption of the Highway Flow, "The Highway Flow in the Craters of the Moon Lava Field; A New Interpretation of Eruption History," was developed by

Interpretive Principles as Applied to Geology

The Six Principles of Interpretation, from *Interpreting Our Heritage* by Freeman Tilden (1977) are stated below. Since Tilden laid down these principles in the 1950's, organizations such as the National Association for Interpretation (NAI) and the National Park Service (NPS) have refined and advanced interpretive methods. The NPS Interpretive Development Program (IDP), for example, views an interpretive program as the cohesive development of a relevant idea that provides visitors with opportunities to form their own intellectual and emotional connections to the meanings inherent in a park resource. Scattered throughout this manual are examples of how each of Tilden's Six Principles might be applied in interpreting geology to CRMO visitors.

1. Any interpretation that does not somehow relate what is being displayed or described to something within the personality or experience of the visitor will be sterile.
2. Information, as such, is not interpretation. Interpretation is revelation based upon information. But they are entirely different things. However, all interpretation includes information.
3. Interpretation is an art, which combines many arts, whether the materials presented are scientific, historical, or architectural. Any art is in some degree teachable.
4. The chief aim of interpretation is not instruction, but provocation.
5. Interpretation should aim to present a whole rather than a part, and must address itself to the whole man rather than any phase.
6. Interpretation addressed to children (say, up to the age of twelve) should not be a dilution of the presentation to adults, but should follow a fundamentally different approach. To be at its best it will require a separate program.

NPS Geoscientist-in-the-Parks volunteer Mary Caress (Caress and Owen, 2005). Throughout the year, nature hikes and teacher workshops presented by park personnel and local experts focus on various geological topics relevant to CRMO. This training manual complements these works by focusing on certain aspects of geology not detailed previously, and by developing interpretive ideas to make the geology more meaningful to the visiting public.

Geological Themes for CRMO

1. Official CRMO Park Themes, from the Long Range Interpretive Plan (LRIP):

VOLCANOLOGY Primary Interpretive Theme

- Craters of the Moon provides opportunities for people to experience a remarkably well preserved volcanic landscape.

Subthemes

- Short of traveling to Hawaii, Craters of the Moon provides one of the finest, most accessible and awe inspiring venues in the United States for people to experience and study volcanism in many different forms.

- Research continues to unravel the many mysteries of this landscape, and new knowledge acquired here helps scientists to better understand volcanic events that have occurred elsewhere.

GREAT RIFT Primary Interpretive Theme

- The Great Rift and its associated features are only the most recent reminders of an awesome series of geologic events that began to shape the eastern Snake River Plain 16 million years ago.

Subthemes

- The seemingly tranquil Snake River Plain conceals a violent geologic past in which mountain ranges were swallowed by unimaginably huge caldera forming eruptions as the North American plate moved over the Yellowstone hotspot. The most recent event created the Yellowstone caldera 640,000 years ago.

- Beginning 15,000 years ago, a great tear in the earth opened up and magma poured through to the surface during repeated episodes leaving behind a legacy of lava flows and other volcanic features. These features can be clearly viewed on many different scales: up close on trails or from distant images from space.

- Ongoing, but subtle, changes continue to affect the geology of Craters of the Moon as gravity, weather, and natural and human activities gradually alter this volcanic landscape.

- Continued stretching of the North American plate in this region combined with high levels of heat in the subsurface and a record of repeated eruptions indicate that there will likely be more volcanic events in the future.

2. Other potential interpretive themes for CRMO, suggested by concepts discussed in this manual:

- The remarkably well preserved volcanic features of CRMO resulted from geologic events that appear to have happened yesterday and will likely continue tomorrow.
- The peculiar landscape of CRMO is very much like the moon’s surface, except that countless insects, animals, and plants call this place home.
- Broken Top cinder cone and its lava flow are two of the youngest features at CRMO and, rather than being barren, have a rich diversity of plant life – in stark contrast to the younger Blue Dragon flow.
- Lava tubes serve as the main avenues for lava flows to travel great distances at CRMO, and they make nice habitats for many plants and animals.
- The Yellowstone Hotspot blasted its way through mountains to form the flat Snake River Plain and left residual magmas that have recently erupted at CRMO.
- The molten lava flows that formed CRMO happened just a “second ago” in geologic time, and tell a story of volcanism that started with passage of the region over the Yellowstone Hotspot and continues as the continent rifts apart along the Basin and Range Province.

CHAPTER 2
Linking Visitors to the Geology of CRMO
The Big Picture: Plate Tectonics

Craters of the Moon National Monument and Preserve (CRMO) is located within two different geologic regions. The local area is the eastern Snake River Plain (ESRP), which is the track of the Yellowstone hotspot and has many old and young volcanic deposits. The larger regional area is the Basin and Range Province, which is a zone of continental rifting containing young volcanic deposits along with long mountain ranges and adjoining valleys formed by crustal extension. Both of the regions likely contribute to the lava fields of CRMO.

This chapter presents basic geological concepts that are important to understanding the volcanic features of CRMO. A brief introduction to why volcanism happens along the track of the Yellowstone Hotspot and within the Basin and Range Province is presented. In-depth information about the geology of those areas is presented in later chapters.

The Earth Has Many Layers

Our planet is made up of several layers that differ in chemical composition and physical state. The major divisions of the earth are the *crust*, *mantle*, and *core*, which differ in chemical composition. Both temperature and pressure increase with depth, which results in the physical differences that further divide these layers into the *lithosphere*, *asthenosphere*, *lower mantle*, *outer core*, and *inner core* (Figure 2.1).

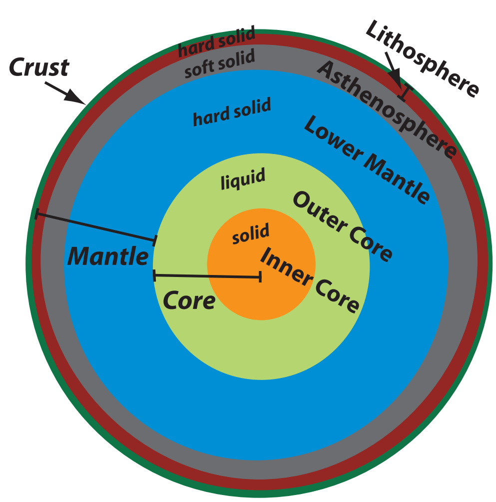


Figure 2.1. The major divisions of the Earth based on chemical composition (left) and differing physical states (right).

Chemical Composition

As the Earth was forming, the planet was very hot and probably nearly entirely molten. Because of gravity, denser elements settled deeper into the Earth than lighter elements. The *crust* is therefore made up dominantly of the lighter rock-forming minerals – silicates (silicon/oxygen compounds) containing aluminum, calcium, potassium, and sodium. The *mantle* is composed primarily of silicate minerals rich in iron and magnesium, comprising rocks such as peridotite. The *core* is composed of dense elements – mostly iron and some nickel.

Physical States

As depth increases within the Earth, both temperature and pressure increase. This creates more divisions as rocks of similar chemical composition behave differently when subjected to increasing temperature and pressure.

A rigid *lithosphere* is made up of the crust and outermost mantle. The lithosphere is the hard outer surface of the Earth that is the coldest layer and under the least amount of pressure. The underlying *asthenosphere* is hotter than the lithosphere and is a soft solid. As pressure increases, it becomes harder for mantle material to melt, even when exposed to higher temperatures. Therefore, even though the *lower mantle* is hotter than the asthenosphere, it is a relatively hard solid because of the higher pressures found at that depth. Plates of lithosphere can be 150 km (100 miles) thick, while the asthenosphere extends from about 150 to 700 km (100-400 miles) depth, and the lower mantle from about 700-2,900 km (400-1,800 miles). The *outer core* is liquid because the high temperatures at depths of 2,900 to 5,100 km (1,800-3,200 miles) are enough to melt iron. Extreme pressures in the *inner core*, found at a depth of 5,100-6,400 km (3,200-4,000 miles), causes this deepest layer of the Earth to be solid.

Plate Boundaries and Hotspots

The circulation of heat within Earth's mantle causes plates of lithosphere to move around on top of the softer asthenosphere, a process known as *plate tectonics*. The interaction between plates at their boundaries causes earthquakes, volcanic activity, and the formation of mountain ranges. There are three different types of plate boundaries: *convergent*, *divergent*, and *transform*. Each type is defined by how a plate moves in relation to an adjacent plate. Most volcanic activity takes place at convergent and divergent plate boundaries. Volcanic activity, however, also occurs within plates, far from any plate boundaries, on top of features known as *hotspots*.

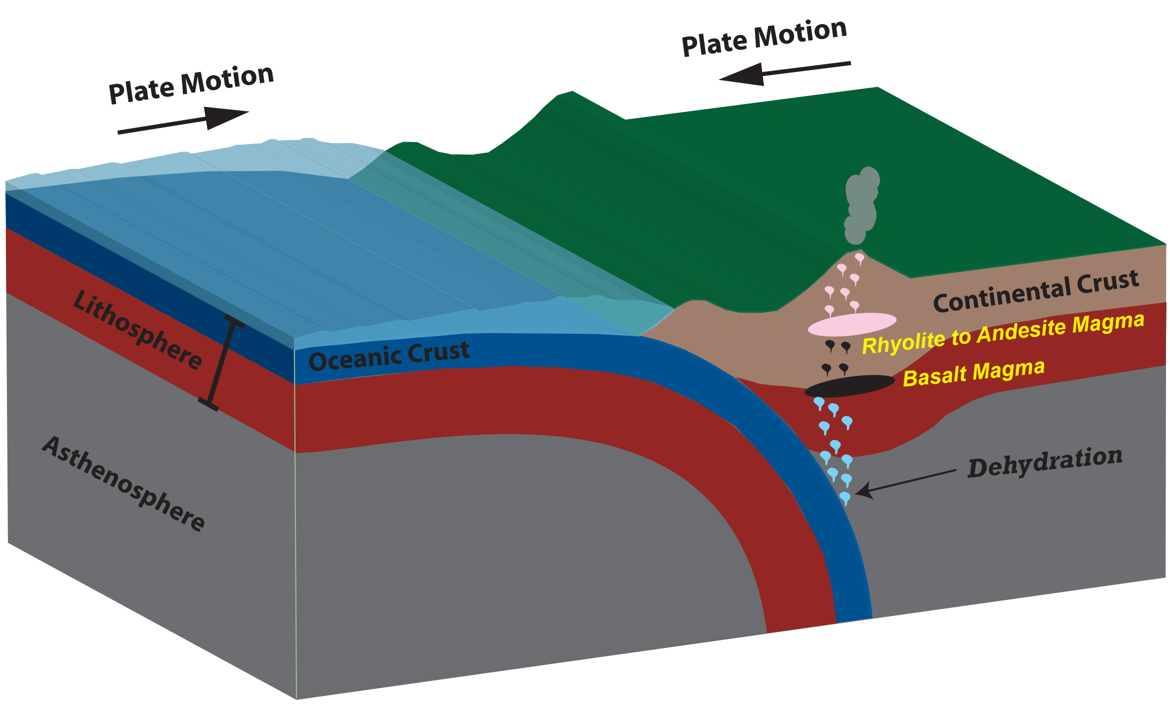
Convergent Plate Boundaries

This type of plate boundary involves two plates colliding with one another. Where a plate capped by thin oceanic crust collides with one that has thick continental crust, the less-buoyant, more dense, oceanic plate is forced underneath the continental plate. This is known as a *subduction zone*. Where two plates comprised of continental crust converge, neither plate will subduct beneath the other. Rather, the thick blocks of continental crust collide, forming a *continental collision zone*, such as the Himalayas where India collides with Asia.

In a subduction zone, the mantle heats up the subducting oceanic plate and literally makes it sweat (that is, it dehydrates). The rising water facilitates melting of the rock in its path, forming volcanoes like the Cascade mountains (Figure 2.2).

As hot liquid rising upward at a subduction zone partially melts the mantle rock (peridotite), basalt magma is formed. Basalt magma has a low silica content (45-50% SiO_2), is dark in color, melts at a relatively high temperature, and has low viscosity (that is, it is very fluid). The basalt magma rises upward toward the surface because it is hot and less dense than the surrounding rock. As it rises into the crust, it continues to melt the surrounding rock. This melted rock changes the composition of the magma so that it ranges from basaltic andesite to rhyolite (Figure 2.2, Table 2.1). These magma types are lighter in color and have higher silica content (55-70% SiO_2) than basalt. They melt at a lower temperature and are much more viscous (stiff). This sluggish magma helps to produce tall, steep-sided volcanoes like those of the Cascade mountains (for example, Mt. Hood in Oregon, Mt. Rainier in Washington, and Mt. Shasta in California) that may experience explosive eruptions, such as the 1980 eruption of Washington's Mt. St. Helens.

Frequent and very large earthquakes occur in *subduction zones* and *continental collision zones*. The two plates rub together and sometimes get stuck due to friction. When they release, large earthquakes are possible (such as the Sumatra earthquake of December 2004, that unleased a devasting tsunami). Earthquakes of smaller magnitude also occur at subduction zones, sometimes due to the movement of magma beneath the surface.



<u>Figure 2.2</u>. In a subduction zone, a plate capped by thin oceanic crust is shoved underneath one with thick continental crust. Water "sweats" (dehydrates) off the subducting oceanic plate and partially melts mantle rock, forming basalt magma. Melting of crustal rocks occurs as the basalt magma rises, forming a variety of magma types ranging from rhyolite to andesite (and sometimes basaltic andesite) magma.

Approximate Silica Composition	40%	50%	60%	70%
Fine-grained (Extrusive)		Basalt	Andesite	Rhyolite
Coarse-grained (Intrusive)	Peridotite	Gabbro	Diorite	Granite

Table 2.1. Igneous rock types according to approximate silica content. Extrusive (volcanic) rocks cool quickly on or near the surface as lava flows, producing mineral crystals that are generally too small to see with the naked eye. Intrusive (plutonic) rocks cool slowly below the surface, producing larger mineral crystals that give the rock a coarse texture.

Divergent Plate Boundaries

A *divergent plate boundary* involves two plates moving away from each other. This occurs along *mid-ocean ridges* and within *continental rift zones*. The Mid-Atlantic Ridge, Juan de Fuca Ridge, and East Pacific Rise are examples of *mid-ocean ridges* where oceanic plates are spreading apart from each other, generating new plate material. CRMO is located within a large continental rift zone called the Basin and Range Province. Thicker continental crust of the North American Plate is starting to pull apart in this large zone of extension that spreads from eastern Oregon and California across Nevada and Idaho, eastward to Utah and southward across parts of Arizona, New Mexico, west Texas, and northern Mexico.

Volcanic eruptions are common at divergent plate boundaries. At mid-ocean ridges, the crust is thin and rising asthenosphere (hot mantle rock) partially melts to form basalt magma. Intrusions of magma into the crust and upper mantle produces new oceanic crust as the plates move away from each other. The global mid-ocean ridge system circles the planet and occurs within all of the major ocean basins.

Volcanic eruptions also occur within continental rift zones, such as the Basin and Range Province. Rising, hot asthenosphere contributes to the high elevations found in the Basin and Range Province – an area with typical elevations above 1,200 m (4,000 ft). The crust stretches and thins as it is elevated. Cracks are formed in the crust of the ESRP where extensional forces are pulling the continent apart. The mantle rock partially melts as it rises and decompresses, forming basalt magma that erupts through systems of cracks known as *volcanic rift zones*. The lava flows of CRMO originated from the Great Rift, one of the many volcanic rift zones in the ESRP.

> "This huge mountain system which includes the Mid-Atlantic Ridge, Indian Ocean Ridge, and East Pacific Ridge is over 60,000 km long and 2,000 km wide (36,000 miles long, 1,200 miles wide). Drain away the oceans and it would be the greatest mountain range on Earth."
>
> from *Volcano Watching: Revised and Updated Edition*, 1997, by Robert and Barbara Decker

> **Continental Rift Zones**
> **vs.**
> **Volcanic Rift Zones**
>
> *Continental rift zones* are regions of continental extension, such as the East African Rift and the Basin and Range Province. Divergence occurs within a plate capped by thick continental crust.
>
> *Volcanic Rift Zones* are regions of upper-crustal extension with eruptions of magma, such as the Great Rift cutting across CRMO and similar features on the flanks of shield volcanoes in Hawai'i and Iceland. Volcanic rifting of the Great Rift is probably related to the continental rifting affecting the broad Basin and Range Province.

Transform Plate Boundaries

Transform plate boundaries involve two plates sliding horizontally past one another. The San Andreas Fault in California is part of a transform boundary where the Pacific Plate is moving northwestward in relation to the North American Plate. These plates grinding past each other produce frequent small-to-large earthquakes that can affect population centers from Los Angeles to the San Francisco Bay area (Figure 2.3). Because plate materials do not descend or rise appreciabley, transform boundaries do not normally produce much volcanism.

Hotspots

Although most volcanic activity occurs at divergent or convergent plate boundaries, substantial volcanic activity sometime takes far from plate boundaries. These regions are known as *hotspots*. The Hawaiian Island chain is the product of a hotspot in the middle of an oceanic plate, while the ESRP and Yellowstone

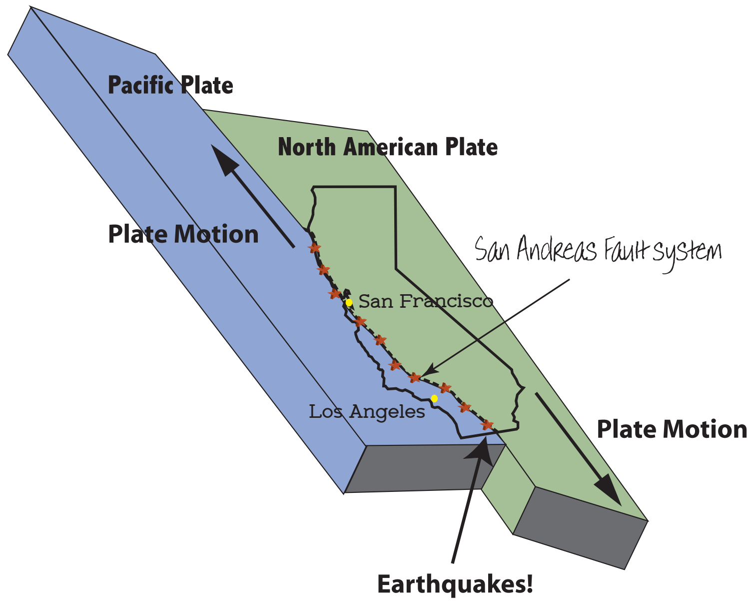


Figure 2.3. The San Andreas Fault in California is part of a transform plate boundary between the Pacific and North American plates. Many earthquakes occur along this fault system, affecting population centers from Los Angeles to San Francisco.

Plateau represent continental hotspot volcanism.

A hotspot is a plume of hot material from the mantle that rises upward and causes volcanic eruptions on an overriding tectonic plate. Similar to volcanic eruptions at mid-ocean ridges, decompression melting of the rising mantle material can cause eruptions of magma onto the surface. As a plate moves over the hotspot, eruptions continue to take place over time, leaving a "string" of volcanic centers across the surface of the plate.

The *Hawaiian Hotspot* has formed the Hawaiian Island chain in the middle of the Pacific Plate. As

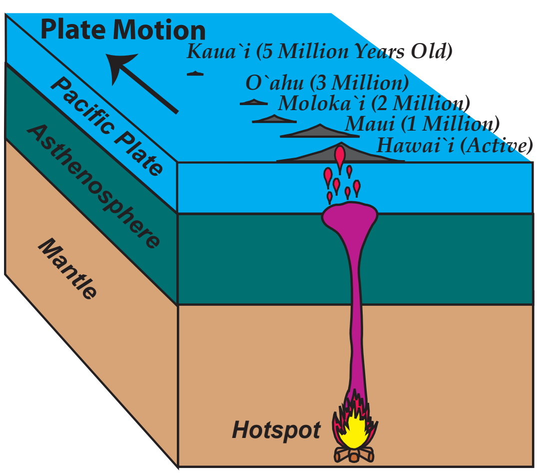


Figure 2.4. The Hawaiian Islands were formed by volcanic eruptions from an oceanic plate overrriding a hotspot. As the Pacific Plate moves over the hotspot, active volcanic islands become inactive, subside as they cool, and their topography lowers as they erode. The Big Island of Hawai'i is currently located above the hotspot and is the most volcanically active of the island chain (modified from Lillie, 2005).

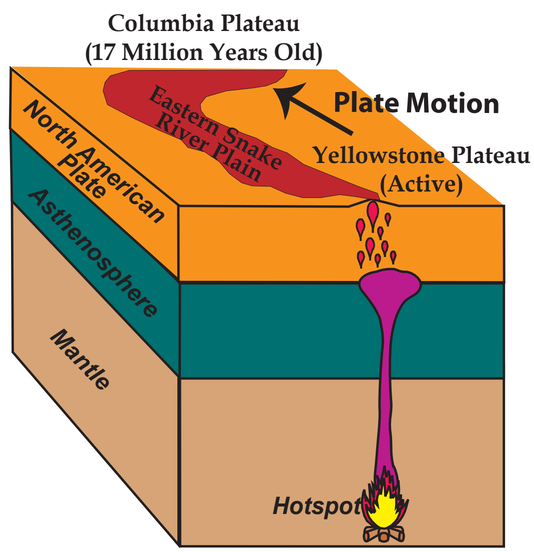


Figure 2.5. The eastern Snake River Plain (ESRP) was formed by volcanic eruptions from the Yellowstone hotspot as the North American Plate moved over the hotspot. The Columbia Plateau in eastern Oregon and Washington may represent the emergence of the Yellowstone plume head, while the ESRP is the track of the tail of the Yellowstone plume across the North American Plate. The Yellowstone Plateau is currently above the hotspot and is volcanically and hydrothermally active (modified from Lillie, 2005).

the plate moves northwestward over time, a line of volcanic islands has been forming. The oldest, least volcanically active, of these islands is the farthest island to the northwest. The youngest (and most active) is the Big Island of Hawai'i, located over the hotspot (Figure 2.4). There is no thick continental crust to melt through, so the rising magma retains its basaltic composition all the way to the surface. Eruptions of basalt are relatively non-explosive and help to form broad shield volcanoes that are not as steep as subduction-related volcanoes formed by rhyolite or andesite magma. Kīlauea is a shield volcano on the Big Island of Hawai'i and is the most active of all the Hawaiian volcanoes. As the plate moves over the hotspot, the corresponding volcanic island becomes inactive, subsides as the plate cools and its topography is lowered further by erosion. Many of the volcanic features of CRMO are similar to those in Hawai'i, because the basalt magma that erupts from the Great Rift is also basaltic.

The *Yellowstone Hotspot* formed the ESRP over time as the North American Plate moved southwestward over the hotspot (Figure 2.5). Yellowstone National Park is currently above the hotspot. Volcanic features of Yellowstone differ from those of Hawai'i because the Yellowstone Hotspot is located beneath a continental plate and a wide range of magma types are produced. Decompression melting of the rising mantle initially forms basalt magma. The basalt magma in turn melts crustal rocks and forms higher-silica (rhyolite) magma. Compared to Hawai'i, eruptions above the Yellowstone Hotspot have been much more explosive and formed large calderas (collapsed areas above partially-emptied magma chambers) across the ESRP. The geysers, hot springs, mud pots, and other hydrothermal features of Yellowstone National Park are the result of the ongoing transfer of heat from the hotspot to the surface. The last major eruption from the Yellowstone Hotspot was a highly-explosive ash cloud that occurred about 640 thousand years ago forming Yellowstone Caldera, a feature about 65 km (40 miles) across, in the central part of the park. Eruptions of less-explosive rhyolite lava flows have occurred in the caldera since then. This ongoing volcanic activity is typical of systems like Yellowstone, which are called resurgent calderas.

"Legends tell of the wanderings of Pele, goddess of fire, chased from her former homes on Kauai, Oahu, and Maui by her sister Namaka, goddess of the sea. Pele's present home is in Halemaumau, the crater of Kīlauea Volcano on the Big Island."

from *Volcano Watching: Revised and Updated Edition*, 1997, by Robert and Barbara Decker

CHAPTER 3
Zooming in on the Geology of the Eastern Snake River Plain

Craters of the Moon National Monument and Preserve is located in the eastern Snake River Plain (ESRP) in central Idaho (Figure 3.1). The numerous basaltic lava flows present within the monument are located along the Great Rift volcanic rift zone (Great Rift), which extends NNW-SSE about 52 mi (84 km) across the ESRP. The Great Rift has the same NNW-SSE trend that is characteristic of extensional features (mountain ranges and adjoining valleys) in this part of the Basin and Range Province. The ESRP and its associated basaltic volcanic centers also lie along the Yellowstone Hotspot track that extends northeast from the Oregon/Idaho/Nevada junction (Owyhee Plateau) to the Yellowstone Plateau of Idaho, Wyoming, and Montana. Modern theories for the origin of volcanism within CRMO relate either to Basin and Range extension, the track of the Yellowstone Hotspot, or a combination of the two (Hughes and others, 1999; Kuntz and others, 1986; Kuntz and others, 1983).

Yellowstone Hotspot

The inception of the Yellowstone hotspot is thought to have occurred approximately 16.5 million years ago with the formation of the first caldera near McDermitt, Nevada. Rhyolite volcanism progressed in a northeastward direction to the Yellowstone Plateau as the North American Plate moved southwestward across the hotspot. Calderas formed along the ESRP, as evidenced by the presence of rhyolite volcanic deposits similar to those found in Yellowstone National Park. These deposits decrease in age to the northeast. A contemporaneous line of volcanism also extends across the High Lava Plains of Oregon, in a northwestward direction, from the same area as the in-

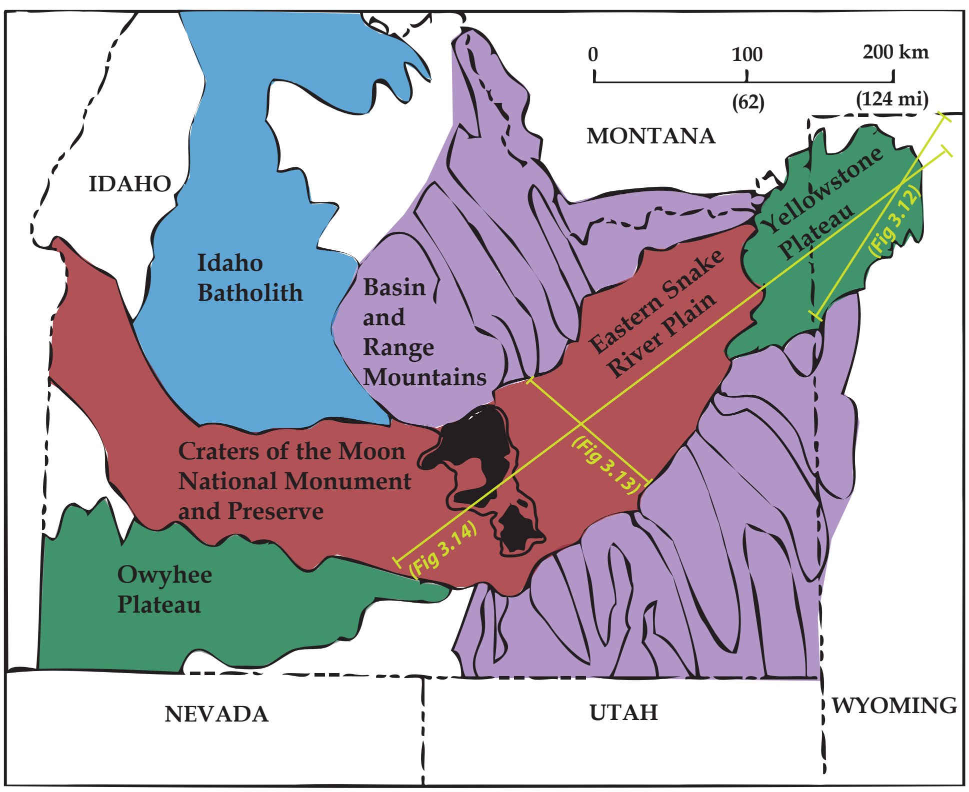


Figure 3.1. Regional setting of Craters of the Moon National Monument and Preserve (CRMO) within the Snake River Plain in Idaho, shown in red (modified from Owen, 2003). Basin and Range mountains are in light purple and show approximate NNW-SSE trend related to extension. The Owyhee Plateau and Yellowstone Plateau are in green. The Idaho Batholith is in light blue. Yellow-green lines show approximate locations for cross sections of the Yellowstone caldera (Figure 3.12), the ESRP (Figure 3.13), and along the ESRP to Yellowstone (Figure 3.14).

ception of the Yellowstone Hotspot (Figure 3.2) (Jordan and others, 2004).

The Yellowstone Plateau has experienced dominantly rhyolite volcanism, with three major eruptions: 2.1 million (Huckleberry Ridge caldera), 1.3 million (Henry's Fork caldera), and 640,000 years ago (current Yellowstone caldera) (Figure 3.3). The Sour Creek and Mallard Lake resurgent domes are areas of uplift representing magma moving close to the surface in Yellowstone National Park (Pierce and Morgan, 1992; Smith and Siegel, 2000).

The track of the hotspot progressed along the axis of the ESRP, which trends across mountains of the Basin and Range Province. Basalt lava flows have filled and covered earlier rhyolite calderas in the ESRP. The CRMO region was, perhaps, a landscape similar to Yellowstone just a few million years ago. A representation of the location of the Yellowstone Hotspot with respect to Yellowstone National Park and CRMO (Figure 3.4) illustrates the early and late stages of volcanism associated with the hotspot and its track across the Snake River Plain (Lillie, 2005).

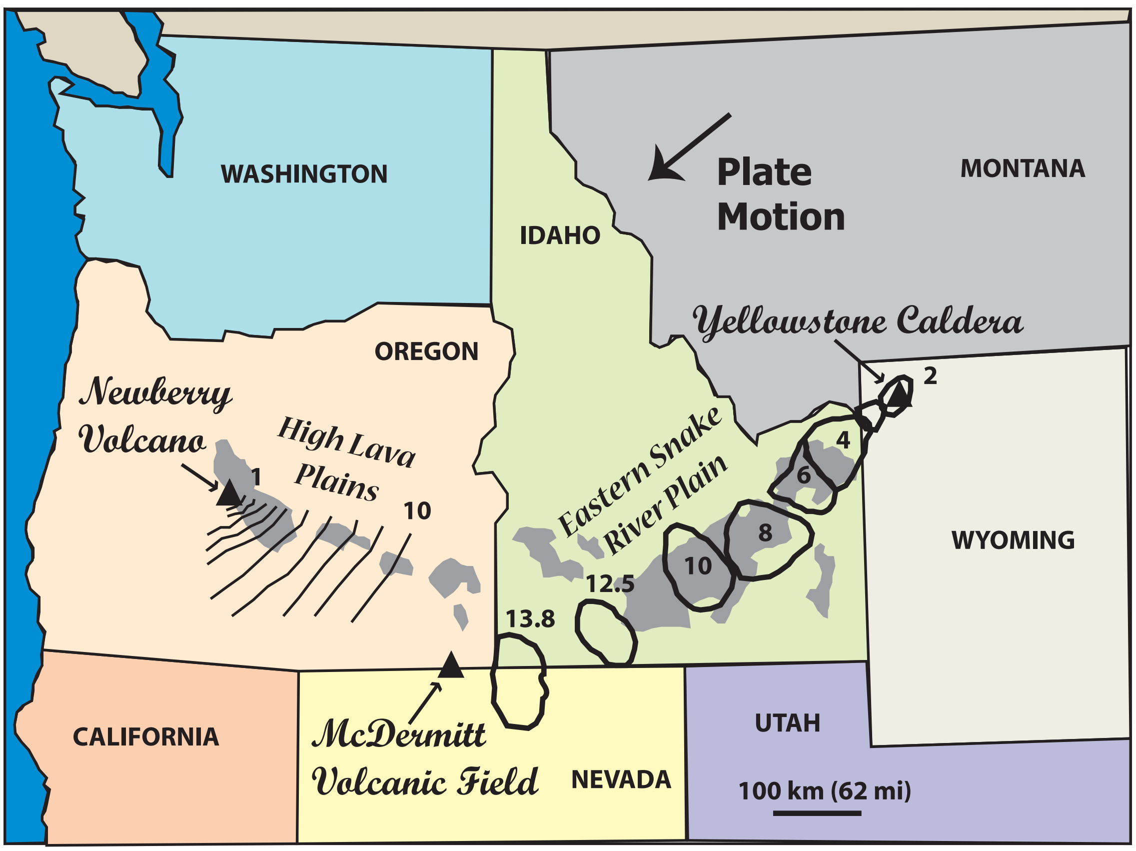


Figure 3.2. The Yellowstone and Oregon High Lava Plains volcanic systems. Younger basaltic cover of the eastern Snake River Plain and High Lava Plains is shown in light gray along with dark circles repesenting the rhyolite volcanism of the Yellowstone hotspot track. Isochrons (lines of equal age) for rhyolite volcanic centers of the High Lava Plains are shown as solid lines (Jordan and others, 2004). Numbers represent approximate ages (in millions of years ago) of initial rhyolite features associated with both volcanic systems (modified from Christiansen and others, 2002; and Jordan and others, 2004).

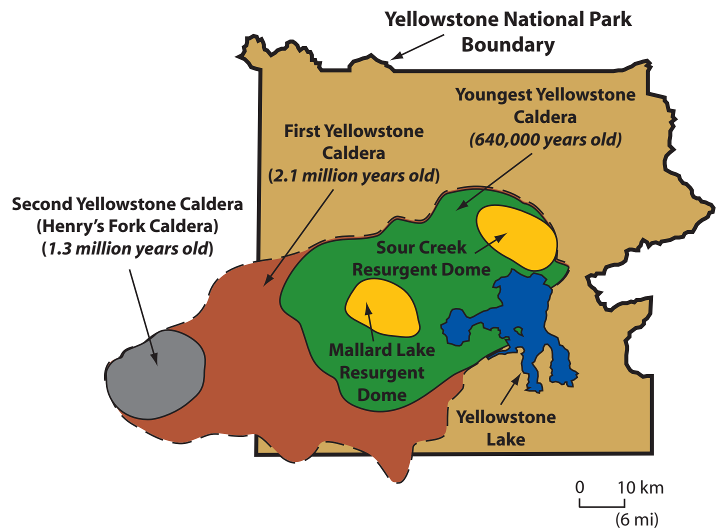


Figure 3.3. Calderas and recent resurgent domes in the Yellowstone Plateau region (modified from Yellowstone National Park, Division of Interpretation, 2003).

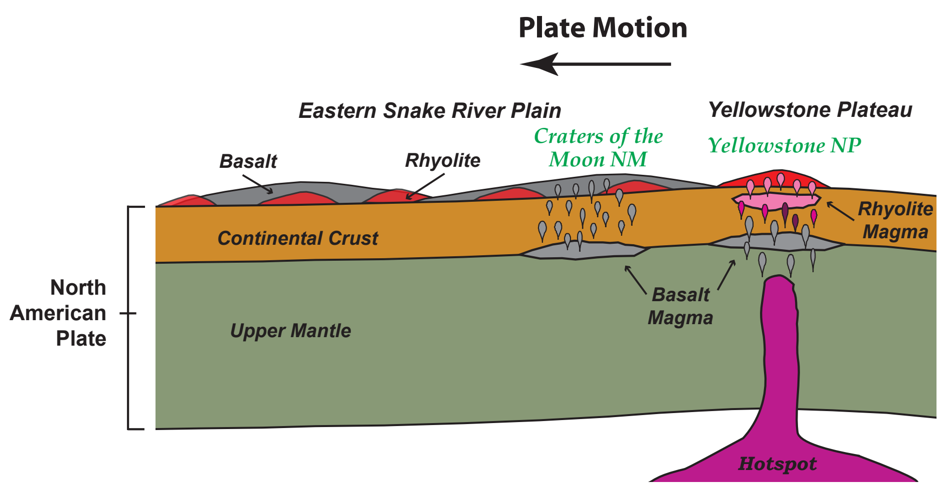


Figure 3.4. Diagrammatic cross section showing the late-stage basalt volcanism (dark shading) occurring at Craters of the Moon National Monument, as compared to the rhyolite volcanism (pink shading) occurring at Yellowstone National Park, which lies directly above the Yellowstone hotspot (modified from Lillie, 2005).

IN DEPTH

Origin and Depth of the Yellowstone Hotspot

Although there are competing theories for the origin of the Yellowstone Hotspot, most researchers agree that hot mantle located under western North America is the most plausible explanation for the Yellowstone volcanic system. Questions remain as to exactly how deep within the mantle the hot material originated and exactly what caused volcanism to progress in the opposite direction across the High Lava Plains in Oregon. Ongoing geologic research may be able to answer some of these questions.

One theory attributes the Yellowstone Hotspot to a plume much like the deep-mantle plume postulated for the formation of the Hawaiian Islands (Pierce and others, 2002; Pierce and Morgan, 1992). Another suggests that the Yellowstone hotspot is a plume that originates at a more shallow depth, within the upper mantle (Christiansen and others, 2002; Christiansen, 2001). The northwest-trending volcanic progession of the Oregon High Lava Plains leads other researchers to doubt a hotspot origin. It is possible, however, that both volcanic systems result from flow of mantle-plume material originating from the same hotspot (Jordan and others, 2004).

Morgan (1971) first theorized that hotspot volcanism, such as that seen in Hawai'i, could result from mantle plumes. This idea was later applied in more detail to Yellowstone volcanism (Pierce and others, 2002; Pierce and Morgan, 1992). Smith and Braile (1994, 1993) attribute the Yellowstone hotspot to a mantle plume due to the following observations: 1) the northeast propagation of increasingly younger (from 16.5 to 0.6 million years old) rhyolite volcanic centers along the ESRP toward the Yellowstone Plateau; 2) a parabolically-shaped ("bow-wave") area of uplift and earthquake activity surrounding the ESRP and "pointing" in the direction of the Yellowstone Plateau; and 3) the increase in elevation from ~1,200 m (4,000 ft) in the western Snake River Plain to ~2,500 m (8,000 ft) in the Yellowstone Plateau. Smith and Braile (1994) do not, however, differentiate between a lower-mantle and an upper-mantle origin in their hypothesis.

Pierce and Morgan (1992) have further explained that the extensive volcanism across southeastern Oregon (High Lava Plains) 16 to 10 million years ago may be due to the hotspot breaking through the overlying Vancouver slab (a section of oceanic plate previously subducted beneath North America) and being diverted to the west. This could explain the difference in apparent velocity of 7 cm/yr (~3 in/yr) of the northeastward track of the hotspot from 16-10 million years ago, and the slower apparent velocity of 3 cm/yr (~1 in/yr) from 10 million years ago to the present. This may also explain the nearly opposite (northwestward) trend of the Oregon High Lava Plains volcanic system compared to that of Yellowstone (Pierce and others, 2002).

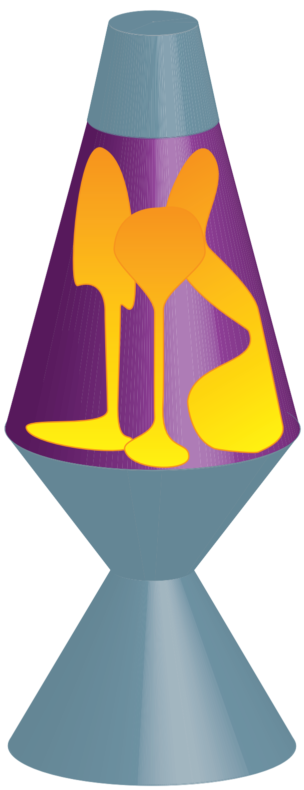


Figure 3.5. A lava lamp can be used to represent the Yellowstone Hotspot. The yellow, semi-solid wax represents the hot mantle material of the hotspot rising upward through the surrounding rock (the purple oil) because the hot wax is less dense than the surrounding oil.

Christiansen and others (2002) and Christiansen (2001) present a theory that the hotspot does not originate in the lower mantle of the Earth, but rather that it was formed by a convective cell (an area of circulation of hot material) within the upper mantle. The timing of the start of Basin and Range extension of the region, approximately 17 million years ago, coincides with the timing of the inception of the hotspot as well as the westwardly-propagating Oregon High Lava Plains volcanic system. However, confusion remains as to which happened first (a "chicken or the egg" conundrum). The amount of Basin and Range extension that has affected the area to the north of the ESRP is much less than the amount of extension of the area to the south of the ESRP. Some seismic studies document plume material only to a depth of approximately 200-250 km (120-150 miles), which is located within the upper mantle. Further studies may shed new light on the issue of deep mantle plume vs. shallow convective cell.

The Yellowstone Hotspot is like a Lava Lamp

A graphic way to think about how the presence of the Yellowstone Hotspot underneath Yellowstone National Park causes volcanic eruptions is to compare the Yellowstone hotspot to a lava lamp. In a lava lamp, when the wax is heated, it expands and rises upward through the surrounding oil because it expands and becomes less dense than the oil (Figure 3.5). Underneath the Yellowstone Plateau, hot mantle material expands and rises upward because it is less dense than the surrounding mantle. It is still solid, but is in a somewhat "plastic" state. As the hotspot material rises to shallower depth, the pressure on it lessens, causing some of the material to melt. Molten magma erupts onto the surface as lava flows. Magma accumulated near the surface provides heat for the geysers, hot springs, and other geothermal features that make Yellowstone National Park such a special place.

Eastern Snake River Plain

Why is the eastern Snake River Plain so low and flat?

The ESRP is a 100-km (60-mi) wide depression that trends northeastward from Twin Falls to Ashton, Idaho (Figure 3.6). Portions of the ESRP were initially uplifted during the early (rhyolite) phase of volcanism; they were heated and expanded as they passed over the Yellowstone Hotspot, much as the Yellowstone Plateau is an uplifted region today (Hughes and others, 1999). As these regions moved southwestward beyond the hotspot, they cooled off and contracted, thus lowering the topography in the eastern Snake River Plain. Dense material was added to the crust in the form of basalt lava flows at the surface and gabbro intrusions deeper within the crust (see Figure 3.13). This weighed the region down, further contributing to the lower topography.

Why does the eastern Snake River Plain still experience basalt volcanism?

The ESRP contains several volcanic rift zones that are parallel to the mountains and valleys of the Basin and Range Province (Figure 3.6), suggesting that the ESRP may be affected by the same extensional forces. The basalt deposits of CRMO mostly formed after the ESRP moved past the hotspot, because by then the crust was depleted in silica and basalt magma was able to flow out onto the surface through cracks formed by Basin and Range crustal extension. The CRMO landscape is thus the product of the North American plate passing over the Yellowstone Hotspot, while subsequently being pulled apart by Basin and Range continental rifting (Hughes and others, 1999).

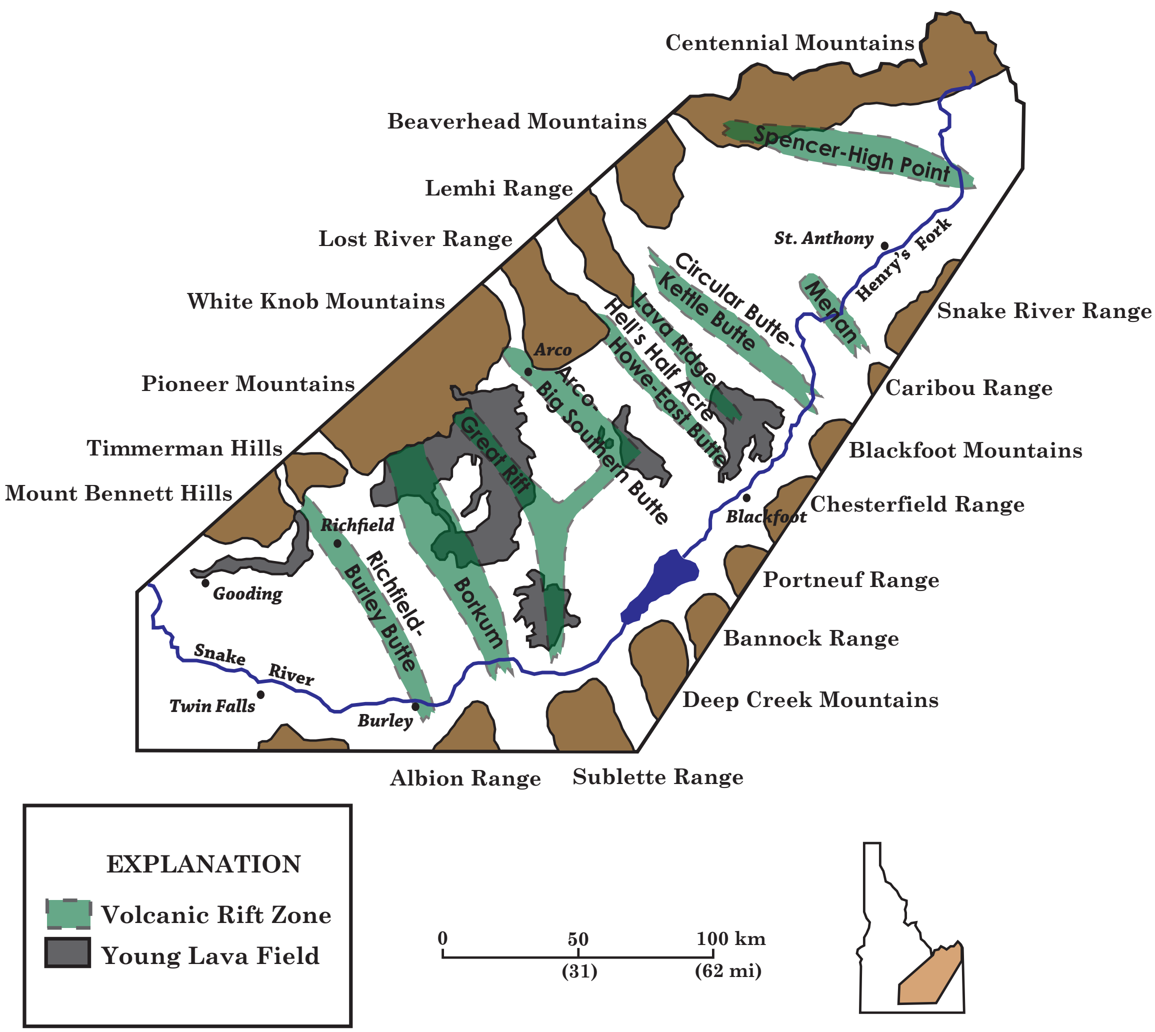


Figure 3.6. The volcanic rift zones of the eastern Snake River Plain show the same NNW-SSE trend displayed by surrounding mountains and valleys of the Basin and Range Province (modified from Kuntz and others, 2002).

Yellowstone Hotspot Carved Out the Eastern Snake River Plain – A Children's Program

Have the children look at a map, similar to the one in Figure 3.7, and ask them what they notice about the mountains to the north and south of the ESRP. They will probably see that the mountains appear to follow the same NNW-SSE trend on both sides of the ESRP. One might conclude the mountains were continuous across the region, but the Yellowstone Hotspot disrupted the continuity of the mountains on the southwest-traveling North American Plate, eventually forming the flat eastern Snake River Plain.

Ask for one volunteer to pretend to be the hotspot (hand him/her a rock that he/she pretends is REALLY HOT, like a hot potato). Then ask for two more pairs of volunteers to be the mountains. They represent the North American Plate and they will move "across" the hotspot. They face each other and form an "A" shape between them (hands joined over head) and stand behind the hotspot. The mountains move until the first pair is over the hotspot, then the hotspot ERUPTS and pushes the lava up through the joined hands of the mountains. Then the mountains sink down and are covered by younger lava flows. The second pair of mountains then moves over the hotspot as well; the hotspot erupts through them too, and they also subside and are covered.

The Sixth Principle of Interpretation

"Interpretation addressed to children (say, up to the age of twelve) should not be a dilution of the presentation to adults, but should follow a fundamentally different approach. To be at its best it will be a separate program."

from: *Interpreting Our Heritage* (1977)
by Freeman Tilden

This Children's Program illustrates Tilden's Sixth Principle. Having kids play out the roles of the various geological components of the Snake River Plain, the interpreter can create an active learning environment often effective with children.

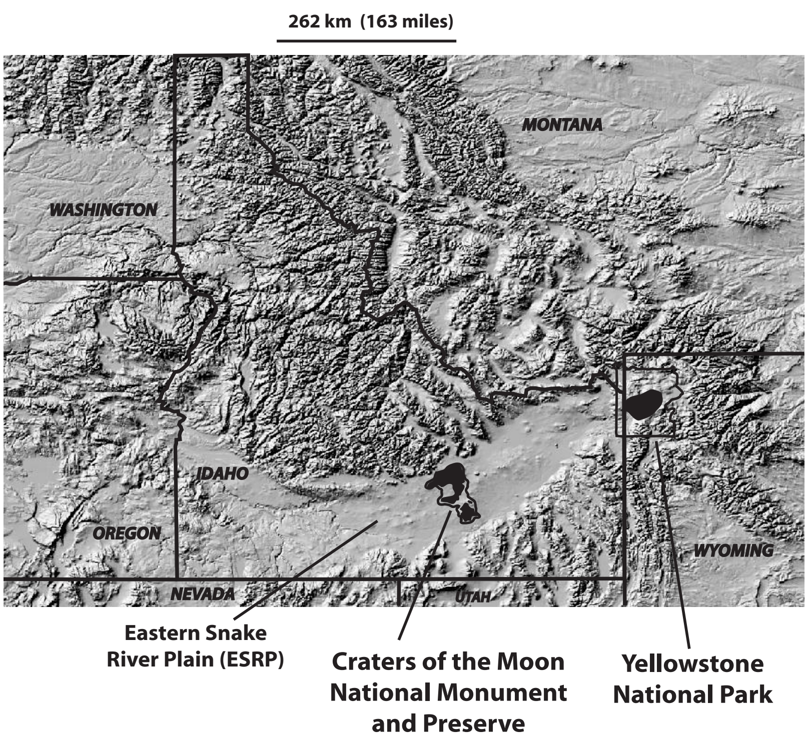


Figure 3.7. Before eruptions of the Yellowstone Hotspot disrupted the area, mountain ranges to the north and south of the eastern Snake River Plain were probably continuous across the plain, evidenced by their similar NNW-SSE trends (image courtesy of United States Geological Survey, National Center for Earth Observation and Science).

What are those other Mountains in the Distance? (Big Southern Butte, Middle Butte, and East Butte)

The isolated mountains (buttes) seen along the ESRP, east of CRMO, are rhyolite domes that formed along a topographic high about 150 km (90 mi) long. This elevated area is known as the Axial Volcanic Zone (Figure 3.8). There is a high concentration of volcanic vents in the area, and the outpourings of basalt and other lavas from these vents contributed to its elevated topography (Hughes and others, 1999).

Big Southern Butte is a *cumulodome* (array of lava domes) which formed about 300,000 years ago and is a prominent feature on the horizon at CRMO (Figure 3.9-3.10). It stands ~800 m (2,500 ft) above the surrounding ESRP and is believed to extend at least 1,000 m (3,000 ft) into the subsurface. Initially, a rhyolite sill (horizontal layer of magma that intruded into the surrounding rock layers) formed. With continued injection of magma, the sill became much thicker, and more rounded than flat. Finally, the rhyolite magma broke through the overlying layers of basalt lava flows on the surface (the north-dipping layers of basalt found on the north side of Big Southern Butte) (Hughes and others, 1999; McCurry and others, 1999).

Middle Butte has an outer surface of approximately 20 south-tilting basaltic lava flows with a probable rhyolite center (geophysical data show that the center is less dense and less magnetic that basalt). This rhyolite core of unknown age probably pushed the basaltic layers upward, but unlike Big Southern Butte, never broke through the basalt. On the surface, only basaltic layers are seen (Figures 3.10-3.11). Middle Butte is assumed to be much older than the surrounding buttes, but an exact age is not known (Hughes and others, 1999; McCurry and others, 1999).

Unnamed Butte is found between Middle Butte and East Butte and is approximately 1.4 million years old. Although seemingly small in size compared to the other buttes, cores drilled into Unnamed Butte show that it extends downward at least 300 meters (1,000 ft) into the surrounding basalt flows on the surface (McCurry and others, 1999) (Figure 3.10).

East Butte is approximately 600,000 years old and has many layers of rhyolite flows stacked on top of each other (rhyolite banding) (Figures 3.10-3.11). Possibly, this rhyolite was too viscous (sluggish) to flow very far from the source (Hughes and others, 1999; McCurry and others, 1999).

Yellowstone National Park contains mostly rhyolite volcanic products, with limited basaltic areas (like Sheepeaters Cliff). Big Southern Butte, Middle Butte, and East Butte are located along the ESRP between CRMO and Yellowstone National Park. This area of the ESRP has both recent basalt lava flows and recent rhyolite features, like the buttes of the Axial Volcanic Zone.

The ESRP connects CRMO to Yellowstone, figuratively and geographically. At CRMO, Big Southern Butte is a major feature on the horizon and is visible from most areas of the park. It peaks visitors' interest to tell them that Big Southern Butte (and the other buttes along the ESRP) are also volcanoes, but are much older and formed differently, and from different types of magma, than the features they see at CRMO. The rhyolites of the Axial Volcanic Zone are most likely a "distillation" (partial crystallization) of higher-silica magmas from the lower-silica basalt magmas common in the ESRP, rather than having melted from the surrounding crust (McCurry and others, 1999).

The Second Principle of Interpretation

"Information, as such, is not interpretation. Interpretation is revelation based upon information. But they are entirely different things. However, all interpretation includes information."

from: *Interpreting Our Heritage* (1977)
by Freeman Tilden

The buttes just east of CRMO can be used to illustrate Tilden's Second Principle, By revealing some intellectual meanings behind information about the buttes, rangers can help visitors understand the variety of volcanic features seen along the ESRP and how they are related to both Yellowstone National Park and CRMO. Volcanic features of the ESRP tie the Yellowstone Plateau to CRMO through a progression from mostly basaltic features at CRMO, to a mixture of rhyolite and basaltic features along the ESRP, and finally to mostly rhyolite features within the Yellowstone Plateau.

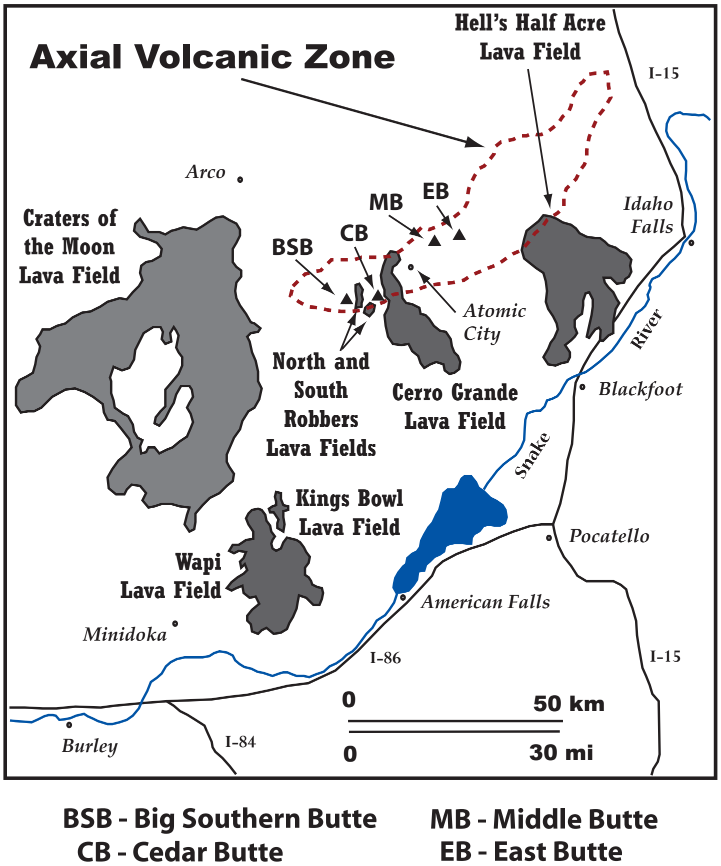


Figure 3.8. *The Axial Volcanic Zone is shown by the red dotted line and extends from west of the Robbers Lava Fields to northeast of the Hell's Half Acre Lava Field. Recent lava fields of the ESRP are shown in dark gray (modified from Hughes and others, 1999).*

Figure 3.9. *Big Southern Butte, as seen from CRMO Loop Road (Photograph by R.J. Lillie).*

Axial Volcanic Zone

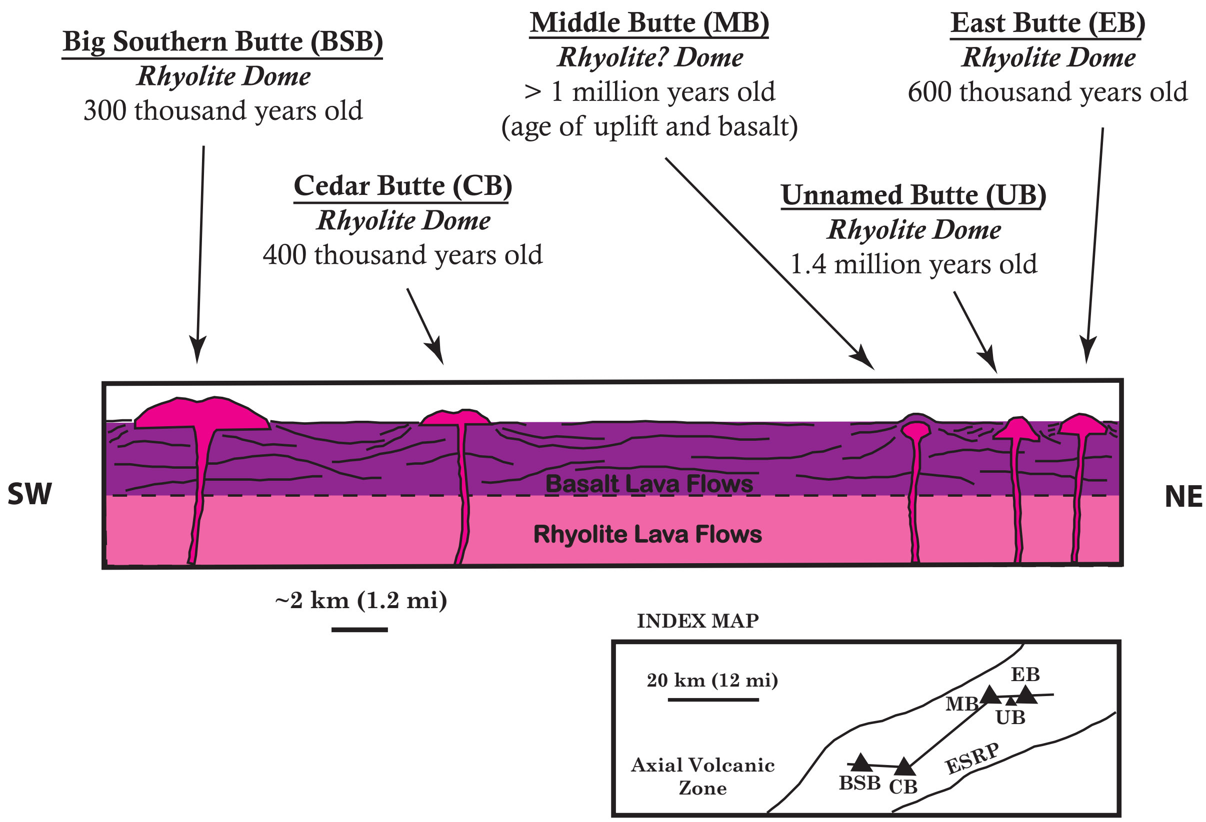


Figure 3.10. The Axial Volcanic Zone contains five buttes of differing ages and varying rhyolite and basalt compositions; these buttes are prominent volcanic features within the ESRP. Layers of basalt lava flows are shown in purple. Rhyolite layers are shown in light pink, underneath basalt layers. Rhyolite intrusions, which formed the buttes, are shown in darker pink. (Modified from Hughes and others, 1999; McCurry and others, 1999).

Figure 3.11. East Butte (left) and Middle Butte (right), looking south from Hwy 20 (Photograph by R.J. Lillie).

IN DEPTH

Crustal Structure of Yellowstone-Snake River Plain Volcanic System

Seismic profiles, earthquake, gravity, and heat flow studies for the Yellowstone-Snake River Plain volcanic system are consistent with a mantle plume hotspot. The asthenosphere shallows toward the Yellowstone Plateau (suggested by high heat flow values), which is consistent with observations of hotspots in other areas of the world. The Yellowstone Plateau has the highest heat flow values in the western United States. Heat flow decreases southwestward along the eastern Snake River Plain (ESRP) as the plate has moved off the hotspot and cooled.

Earthquake studies show the crust is being stressed as the North American Plate moves over the Yellowstone Hotspot. As the topography above the hot region elevates, it stretches and cracks, causing a "parabolic" region of faults and associated earthquakes.

Low gravity readings and high heat flow values suggest the presence of very hot mantle beneath Yellowstone National Park. Such geophysical observations are consistent with the theory of a mantle plume hotspot underlying the Yellowstone Plateau. Representative cross-sections of three areas within the Yellowstone-Snake River Plain volcanic system show gravity values, seismic velocities, and thicknesses of the various crustal layers consistent with passage of the region over a hotspot (Figures 3.12-3.14).

Cross-Sectional Views of the Yellowstone – Eastern Snake River Plain Region

Studies of the velocity of seismic waves as they pass through the Earth (seismic refraction) help to interpret the depths to the boundary between the upper and lower crust, and to the boundary between the crust and mantle (known as the Mohorovicic Discontinuity, or "Moho"). Studies of how seismic waves bounce back from different boundaries (seismic reflection) help to image the geology of the upper crust including layering, faults, and other structures within the crust. The 1978 Yellowstone-Snake River Plain Seismic Profiling Experiment revealed several crustal layers of differing seismic velocities within a crust that is thicker underneath the ESRP and Yellowstone Plateau than it is beneath the northern Basin and Range Province (Smith and others, 1982).

Gravity studies in the ESRP and Yellowstone Plateau reveal that hot mantle is causing the high heat flow and partial melting that lead to magma chamber formation. The pull (acceleration) of the Earth's gravity tends to increase in regions underlain by dense rock, and decrease where the underlying rock is less dense. Extremely low gravity values on the Yellowstone Plateau suggest that the region is underlain by hot, expanded material that has low density, consistent with the hotspot idea. This interpretation is further supported by measurements of heat flow that are almost twice as high as values observed in surrounding regions of the Basin and Range Province (Mabey, 1982).

The Yellowstone "Parabola of Death"

Waves form in the water immediately in front of and to the sides of a boat, extending gradually outward behind the moving boat. The parabola-shaped region of elevated topography and increased seismicity surrounding the Yellowstone Hotspot has a shape very similar to that of the wake of the boat.

Cross Section of the Yellowstone Plateau

Seismic refraction studies reported by Smith and Braile (1993), which expanded on the experiment detailed by Smith and others (1982) and Braile and others (1982), revealed mantle-derived, basaltic intrusions at the base of the crust beneath Yellowstone. A crust-mantle boundary (Moho) that is 40-45 km (25-28

Seismic Velocities Vary with the Type of Rock

When considering how fast seismic waves travel through different types of rocks, it can be helpful to keep in mind some typical seismic velocities for common rocks and some other materials. Compressional (sound) waves move through the air at a speed of about 320 m/sec (1,100 ft/sec). They move through water at about 1.5 km/sec (5,000 ft/sec).

As materials become harder (more rigid), seismic waves move faster through them. Different rock types have typical ranges of seismic velocities – about 2 km/sec (~7,000 ft/sec) for loose sand or mud, 2-5 km/sec (7,000-16,000 ft/sec) for sedimentary rocks, 4-6 km/sec (13,000-20,000 ft/sec) for volcanic rocks such as rhyolite and basalt, 5-7 km/sec (16,000-23,000 ft/sec) for intrusive rocks such as granite and gabbro, and ~ 8 km/sec (26,000 ft/sec) for mantle rock (peridotite).

When rocks are heated, they become softer (less rigid). This causes seismic waves to slow down – hence the low seismic velocities observed for rock heated by the Yellowstone Hotspot. When rocks partially melt, they tend to lose much of their rigid, solid structure; low seismic velocities are thus thought to indicate the presence of magma chambers beneath Yellowstone National Park.

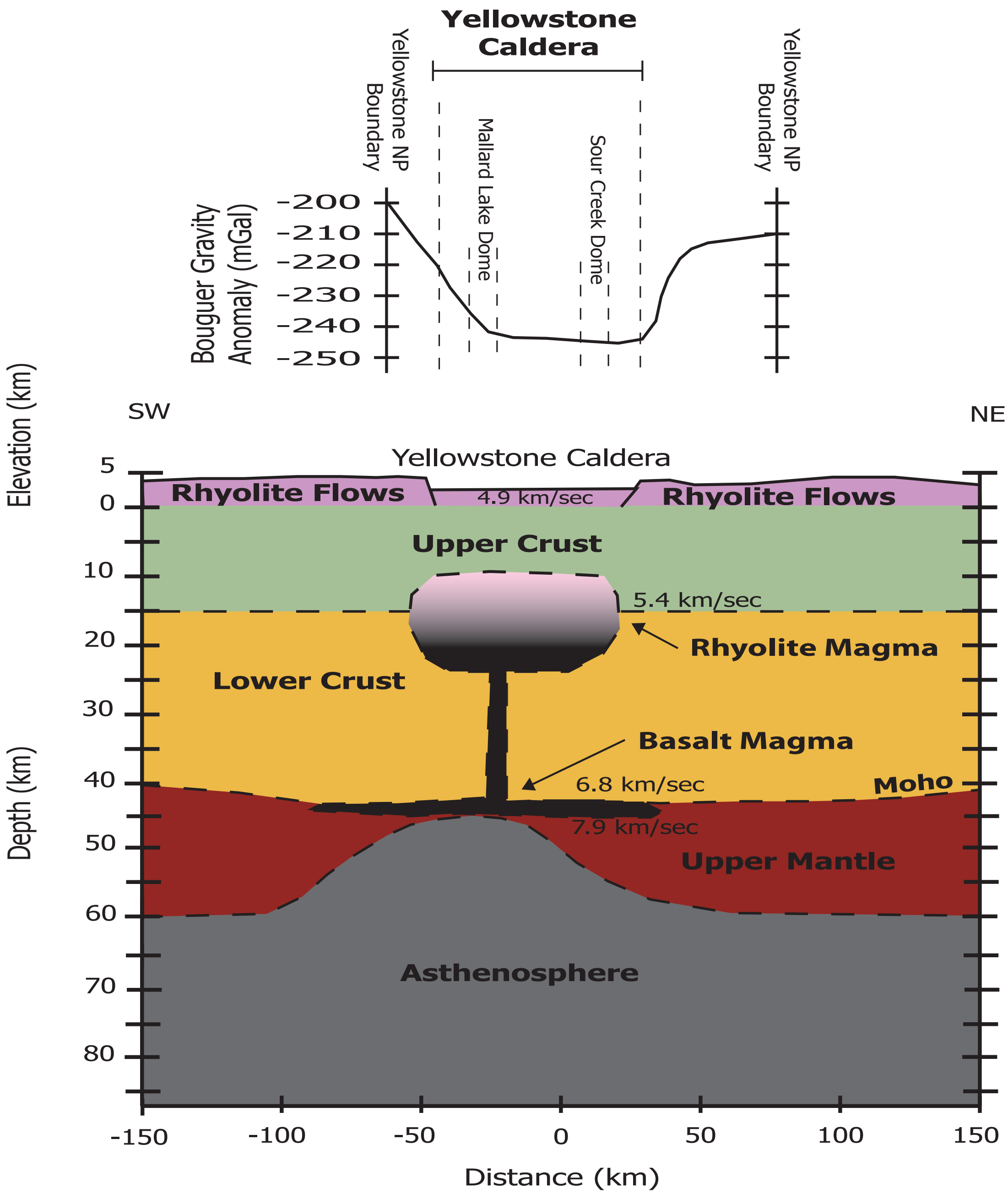


Figure 3.12. Idealized southwest to northeast section line across Yellowstone National Park (location in Figure 3.1). Seismic velocities and thicknesses of layers are from Smith and Braile (1993). The inferred location of the crustal magma chamber is shown with basalt magma (black) at the bottom, grading to rhyolite magma (pink) at the top. Bouguer gravity anomaly profile is from Smith and Braile (1994). The low gravity values across Yellowstone Caldera indicate low-density material beneath the region (hot, expanded mantle and partially-melted crust).

miles) deep indicates that the crust is about the typical thickness for a continent (Figure 3.12).

Seismic reflection profiles and side-scan sonar across Yellowstone Lake, which is mostly located within Yellowstone Caldera, indicate the presence of heat and/or dissolved gases at a shallow depth. Numerous explosion craters, as young as a few thousand years, are apparent on the lake bottom, indicating continuing volcanic activity. Fissures found on the lake bottom reveal roughly north-south orientations similar to trends seen in the surrounding Basin and Range Province. This suggests that the Yellowstone Plateau is experiencing continental extension similar to the northern part of the Basin and Range Province, including the CRMO region (Morgan and others, 2003).

High heat flow occurs at the Yellowstone Plateau. Decrease in gravity values toward the center of Yellowstone National Park (Figure 3.12) correlate with the extremely high heat flow within the Yellowstone Caldera (Smith and Braile, 1994).

Depths of earthquakes and displacements along faults reveal the stresses associated with the Yellowstone Hotspot (Waite and Smith, 2004). Most of the faults northwest of the Yellowstone Caldera are oriented approximately NNW-SSE, while faults southeast of Yellowstone Caldera are oriented approximately north-south. This would be an expected result of roughly east-west directed extensional forces that are acting on the Basin and Range Province north and south of Yellowstone. The majority of the earthquakes occurring within Yellowstone (~99.6%) are small (less than magnitude M4). The 1959 M7.5 Hebgen Lake earthquake and the 1975 M6.1 Norris Junction earthquake are the two largest historic earthquakes of the area and reflect fault orientations of N-S and NE-SW, respectively (Waite and Smith, 2004).

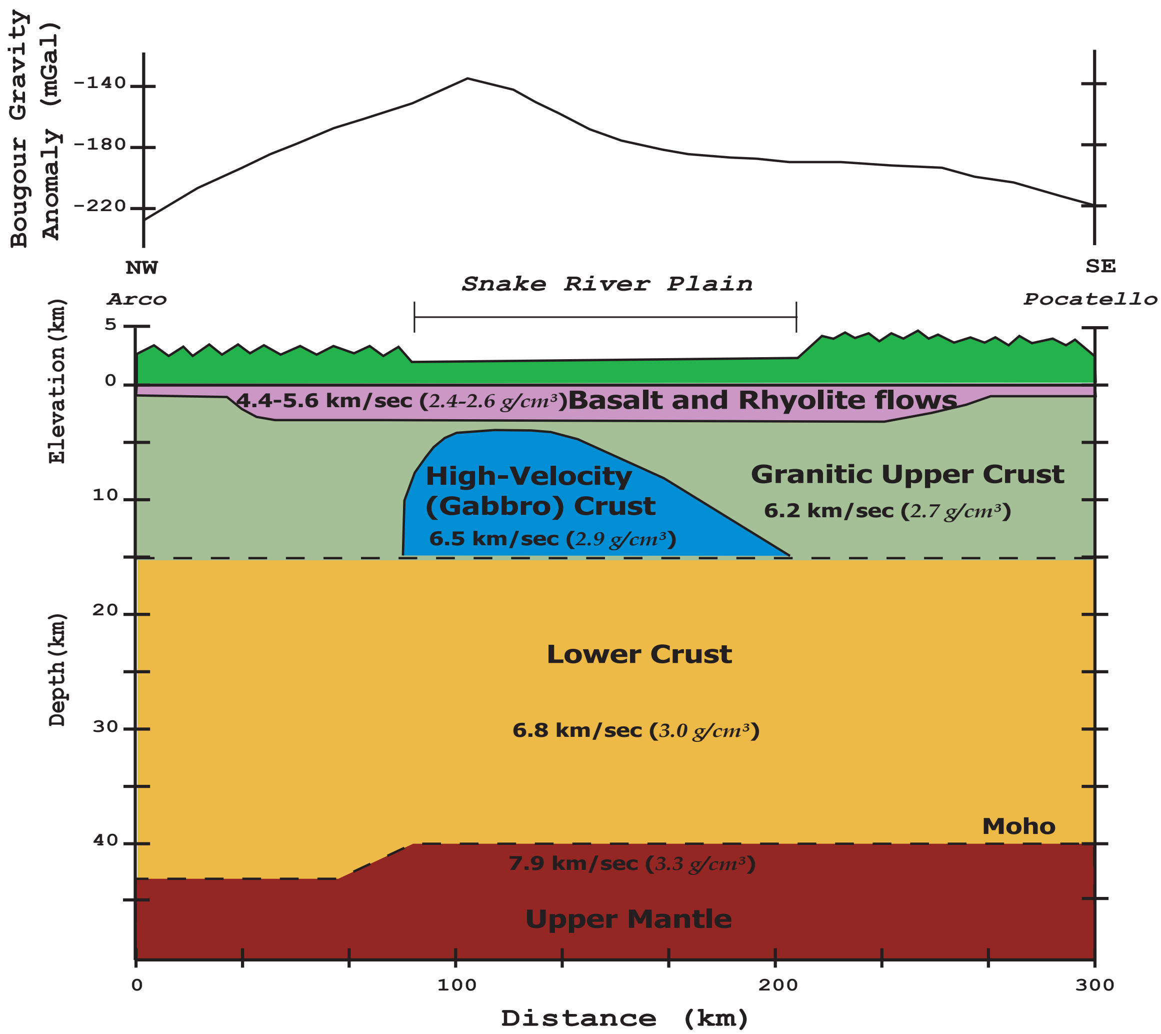
Cross Sections of the Eastern Snake River Plain

Smith and Braile (1993) detailed the following features depicted in Figures 3.13-3.14: 1) a 1 km (0.6 mile) thick layer of basalt flows above a 2-3 km (1-2 miles) thick layer of rhyolite flows in the ESRP, with seismic velocities ranging from 4.5 to 5.6 km/sec (15,000-18,000 ft/sec); 2) a layer of granite composition upper crust, similar to undisturbed areas outside the ESRP, with a velocity of 6.2 km/sec (20,000 ft/sec) that ranges from very thin to 15 km (9 miles) thick; 3) an anomalous mid-crustal layer with a high velocity of 6.5 km/sec (21,000 ft/sec) that underlies the entire ESRP between 8 km (5 miles) and 18 km (11 miles) depth (approximately 10 km [6 miles] thick), interpreted as an intruded basaltic body that probably is the source of continuing basalt volcanism along the ESRP; 4) a relatively uniform lower crust with a velocity of 6.8 km/sec (22,000 ft/sec) that is similar to that of the surrounding Basin and Range Province; and 5) a crust-mantle boundary (Moho) that is 40-45 km (25-28 miles) deep, representing crust that is about the average thickness for a continental region.

Compared to the surrounding regions, earthquake activity is low within the ESRP. Even though the ESRP seems to be experiencing similar extension to that of the Basin and Range Province, prominent faults are not common within the ESRP. Instead, the crustal extension causes fissures, such as those within the Great Rift, through which basaltic magma occasionally rises to the surface.

Bouguer gravity anomalies on the edge of the ESRP are around -220 mGal, increasing to -140 mGal in the middle of the ESRP (Smith and Braile, 1993) (Figure 3.13). The overall negative gravity values are due to the presence of hot, low-density mantle beneath the Basin and Range continental rift zone. The increase in gravity toward the middle of the ESRP suggests high-density gabbro intrusions into the crust of the SRP; gabbro is the intrusive equivalent of the basalt that continues to erupt along the ESRP.

High heat flow is observed for the entire Basin and Range Province, due to hot mantle (shallow asthenosphere) related to continental rifting (Mabey, 1982). The very high heat flow resulting from the Yellowstone Hotspot decreases from the Yellowstone Plateau southwestward along the length of the ESRP, corresponding to the cooling and subsidence of the North American Plate as it moves away from the Yellowstone Hotspot.



<u>Figure 3.13</u>. Results of seismic and gravity studies, adapted from Smith and Braile (1993), as a section crossing the Snake River Plain from Arco to Pocatello, Idaho (location in Figure 3.1). The numbers within layers without parentheses are seismic velocities, while those with parentheses are densities. The cross section shows a general increase in the seismic velocity and density of layers with depth. A relatively high-velocity and high-density zone in the upper crust along the Snake River Plain is thought to represent an abundance of gabbro (intrusive equivalent of basalt). Bouguer gravity anomaly values of -140 mGal to as low as -220 mGal reflect hot, expanded mantle beneath the Basin and Range-Yellowstone region. The rise in gravity values toward the center of the Snake River Plain is due to the high-density gabbro within the crust.

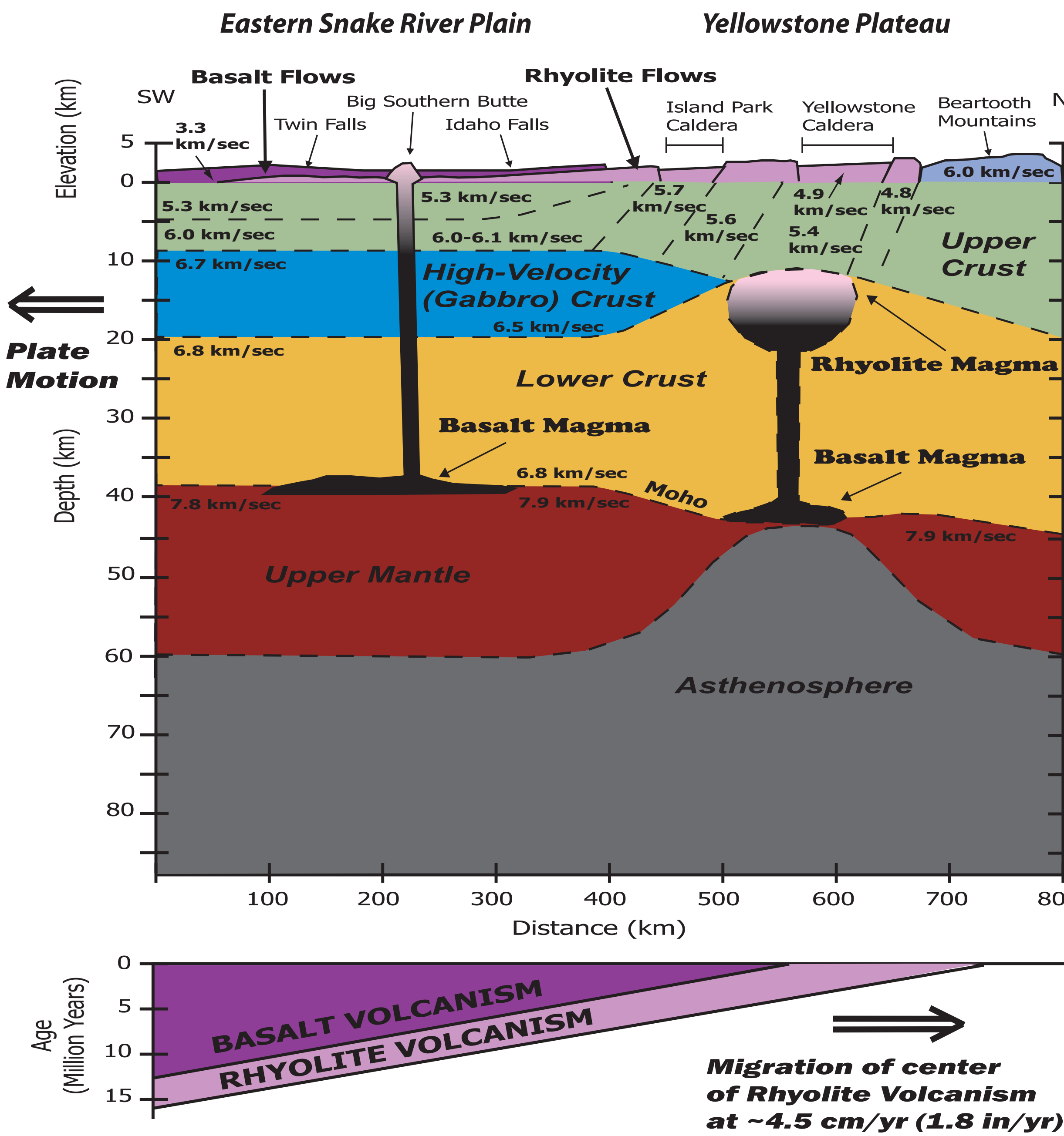


Figure 3.14. Results of seismic velocity studies, adapted from Smith and Braile (1993), plotted as a cross section along the axis of the ESRP southwest to northeast from Twin Falls, Idaho to Yellowstone National Park (location in Figure 3.1). The lower diagram illustrates that rhyolite volcanic deposits beneath the ESRP are progressively younger toward the Yellowstone Plateau, and that overlying basalt flows are found along the ESRP.

Basin and Range Extensional Province

The Basin and Range Province is an area of active continental extension centered between eastern California and Utah. This area is defined by long mountain chains, trending roughly N-S, separated by valleys (Figure 3.15).

Figure 3.1 shows the regional setting of CRMO within the ESRP and the NNW-SSE trend of its volcanic rift zones that is similar to the trend of Basin and Range mountains and valleys to the north and south of the ESRP. An accelerated period of Basin and Range continental extension started approximately 16 million years ago in Nevada, and had spread to eastern Idaho by approximately 2 million years ago (Rodgers and others, 1990). These ages are similar to those associated with the inferred progression of the North American plate over the Yellowstone hotspot, illustrating the difficulty of distinguishing whether features are due to continental rifting, hotspot activity, or a combination of the two.

East-west extension of the continent in the Basin and Range Province results in normal faults, along which mountain ranges rise and valley floors drop (Figure 3.16). The crust stretching in this way accommodates the plate divergence that has begun to affect the region – plate motion that may eventually open into a full-blown ocean basin!

Basin and Range extension was recently active in the Lost River Range, to the northeast of CRMO (Figure 3.6). On October 28, 1983, a magnitude 7.3 earthquake occurred along the Lost River Fault in the vicinity of Borah Peak. The fault scarp is approximately 34 km (21 miles) long and can be seen from Hwy 93 for many miles. The height of the fault scarp is as much as 5 m (16 feet). Trenching studies performed before and after the Borah Peak earthquake on some of the Lost River Range fault scarps reveal that earthquakes have occurred on the Lost River Fault numerous times in the past, possibly of similar magnitude and producing similar-size fault scarps (Crone, 1987; Haller and Crone, 2004). The Borah Peak earthquake is evidence that Basin and Range extension continues to affect the ESRP region. Interpretation of the geology of the Basin and Range Extensional Province, along with other regional geology concepts of CRMO, helps park visitors to appreciate that the region is geologically active and will continue to experience both earthquake and volcanic activity in the future.

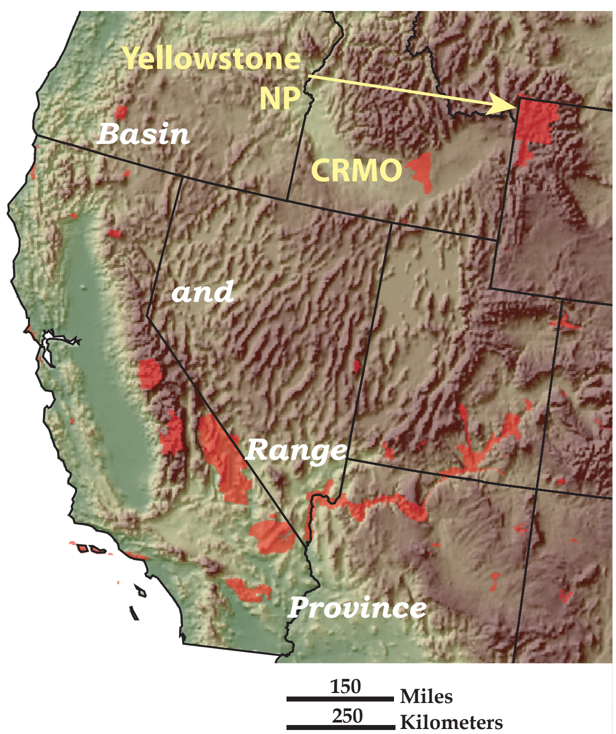


Figure 3.15. Topography of the Basin and Range Province. National Park Service sites are shown in red. (Modified from Lillie, 2005).

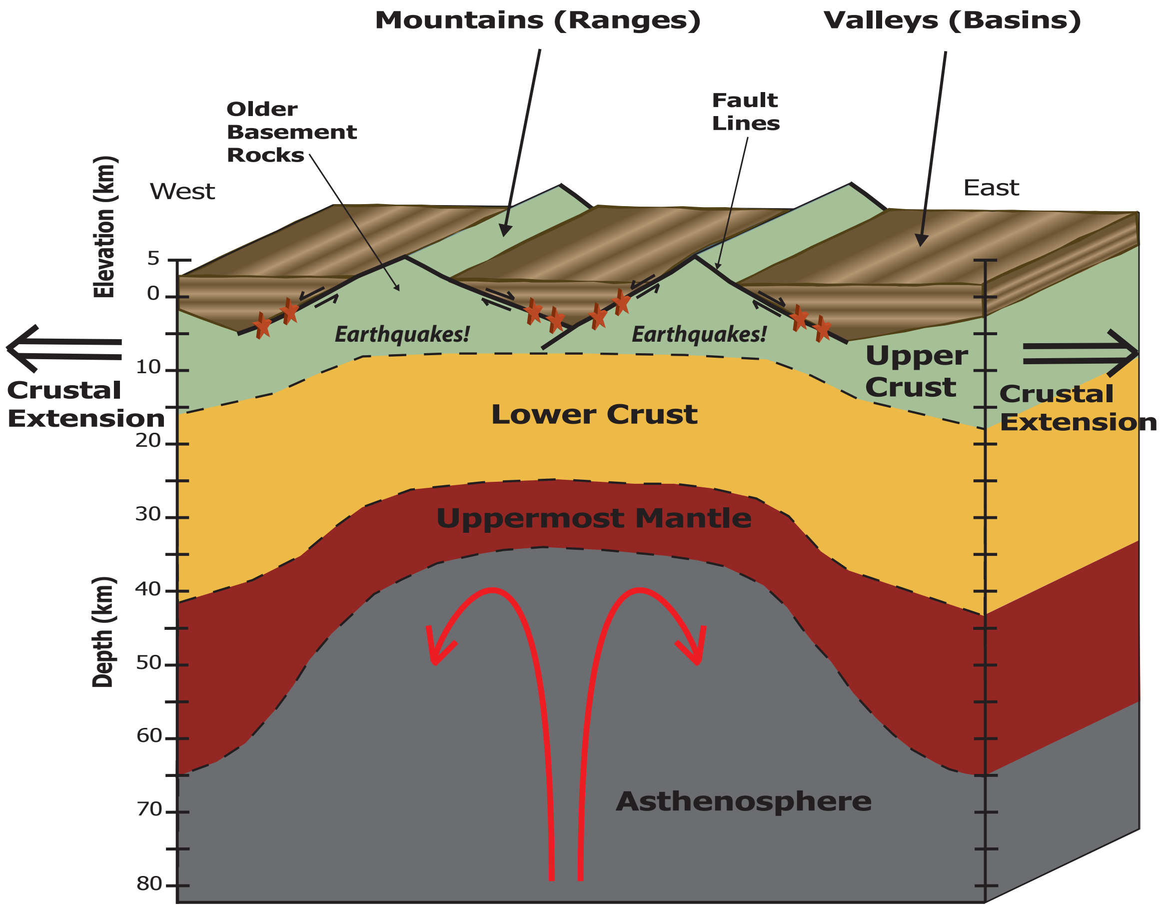


Figure 3.16. Idealized cross section of crustal blocks of the Basin and Range Province. Earthquakes occur on faults that separate uplifted mountain ranges from downdropped rift valleys. Black arrows show that the direction of crustal extension is perpendicular to the trend of the mountain ranges and red arrows portray convection of hot mantle (asthenosphere).

About the Borah Peak Earthquake

The Borah Peak earthquake was one of the largest historical earthquakes in the United States. It was caused by the crustal extension that is ripping apart the Basin and Range Province. During the Borah Peak earthquake, the Lost River Valley dropped about 2.5 m (8 feet) and the Lost River Mountain Range rose 1/3 to 2/3 m (1 to 2 feet). This formed a series of fault scarps extending 34 km (21 miles) along the Lost River Valley that are still visible (Figure 3.17). A young girl standing on the fault scarp in 2005 (Figure 3.18) illustrates that, even 22 years after the earthquake, you can still see the 2 to 3 m (6 to 9 ft) of vertical displacement!

The First Principle of Interpretation

"Any interpretation that does not somehow relate what is being displayed or described to something within the personality or experience of the visitor will be sterile."

from: *Interpreting Our Heritage* (1977)
by Freeman Tilden

The account below from the Mackay, Idaho, resident is a vivid portrayal of Tilden's First Principle of Interpretation. Considering the personal experiences of an earthquake victim helps visitors imagine the reactions they might have to such an unexpected and dramatic geologic event. The account provides an opportunity for visitors to make their own intellectual and emotional connections to the power of the Earth and its effects on peoples' lives.

Figure 3.17. *The fault scarp from the Borah Peak earthquake of 1983 is shown in the center of this photograph, taken in 1985, disrupting Doublespring Pass Road. Mountains of the Lost River Range are in the background (Photograph by R.J. Lillie).*

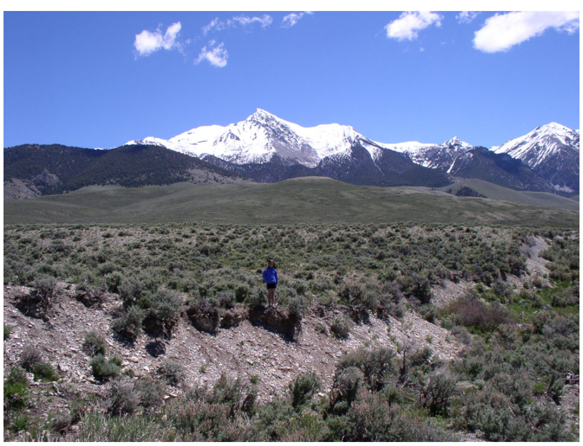


Figure 3.18. *In 2005, the Borah Peak fault scarp is still very well preserved along the Lost River Valley. For scale, note the approximately 1.4 m (4 1/2 ft) tall girl standing on top of the fault scarp. Borah Peak is in the background. (Photograph by T. Stout).*

Experiences of a woman living near Mackay, Idaho, who was in the bathtub when the earthquake began at 8:07 A.M Mountain Standard Time on October 28, 1983. Two people were killed in nearby Challis.

"When I heard the roar and I saw the walls begin to wave, I stood up and grabbed my towel. The next thing I remember, (I) was lying on the bathroom floor with my towel still in my hand and my legs hanging on the inside of the bathtub, and the rest of me lying on the floor. I do not know how I missed hitting my head on either the sink or the hot water heater as I fell out. I was unable to get up during the quake, and so I laid there listening to my dishes falling out of my cupboard and shattering on the kitchen floor. I kept telling (my husband), 'Get the boys,' and I kept hearing (him) yell back to me, 'Get out of there.' I kept telling him that, in my most womanly manner, I just couldn't because I didn't have a thing to wear. After realizing (I wasn't going to be able to get my bathrobe on), my pride left, and so did I.

"(My husband) was on the telephone at the time the quake hit, and our then two-year-old son, Samuel, was standing in front of the refrigerator. (He) threw the phone and with strength he doesn't know where came from, pushed the refrigerator back, or we would have had another fatality in the earthquake.

"The furniture in our bedroom was flying, the chest of drawers fell over on the baby's crib, the bookshelves flew, everything on the bookshelves flew. The TV, sitting on the dresser, went from one side of the room to the other."

Adapted from an interview with an earthquake survivor, Sara Beth Haroldsen, performed by Fred May, Utah Division of Comprehensive Emergency Management; available at www.seis.utah.edu/NEHRP_HTM/1983bora/i1983bo1.htm.

CHAPTER 4
Local Geology of Craters of the Moon National Monument and Preserve

This chapter discusses the geology of the Great Rift Volcanic Rift Zone (Great Rift) and the Craters of the Moon (COM) lava field. Many outstanding features of fluid, basaltic volcanism can be experienced by visitors to CRMO: pāhoehoe and ´a´ā lava flows, cinder cones, spatter cones, lava tube caves, lava bombs, cinders, and much more. By comparing the geology of this region to features formed by recent volcanism in Hawai'i and Iceland, park staff can help visitors connect both intellectually and emotionally to the landscape that surrounds them when they visit the park.

The Great Rift Volcanic Rift Zone

The Great Rift is a volcanic fissure system approximately 80 km (50 miles) long within the eastern Snake River Plain (ESRP) (Figure 3.6). The Great Rift trends in a NNW-SSE direction, parallel to the trend of other volcanic rift zones of the northeastern Basin and Range Province. Approximately 25 cinder cones and many spatter cones have developed in the Craters of the Moon lava field from the vent system of the Great Rift due to pyroclastic eruptions of basaltic magma. The Great Rift is also composed of hundreds of fissures and spatter ramparts, and at least 62 lava flows within three lava fields (Kuntz and others, 1987). Most

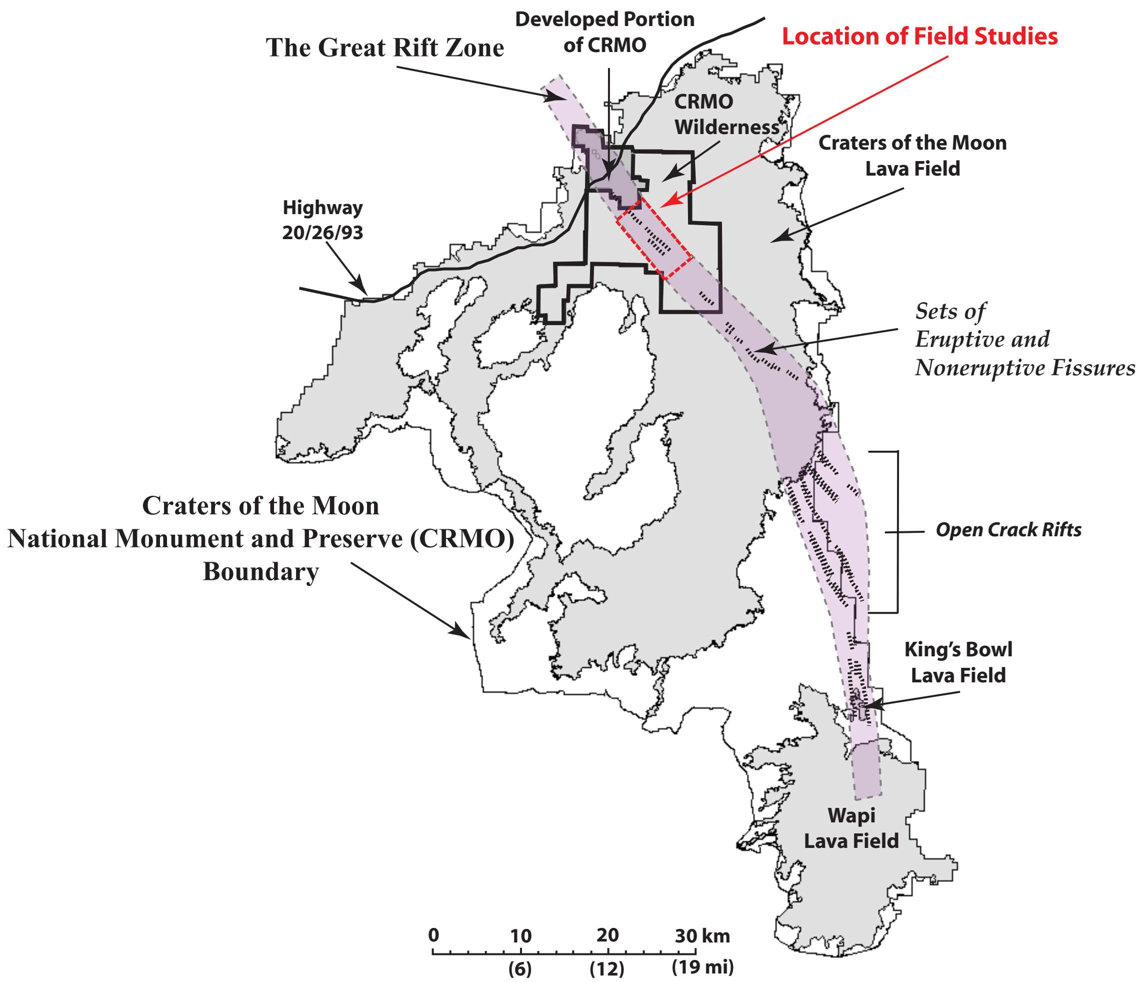


Figure 4.1. The three young basalt lava fields of the Great Rift are shown – Craters of the Moon (COM), King's Bowl, and Wapi. The boundary of the original Craters of the Moon National Monument (bold outline) was expanded in 2000 (lighter outline) to include all three lava fields and now defines the boundary of Craters of the Moon National Monument and Preserve. The diagonal line segments show prominent eruptive and non-eruptive fissures. The area of field studies (red outline) is detailed in the "In Depth" section of this chapter (modified from Kuntz and others, 1986).

of the Great Rift lies within the expanded boundaries of CRMO.

The Great Rift contains three young basaltic lava fields – Craters of the Moon (COM), King's Bowl, and Wapi (Figure 4.1). The COM lava field formed over the past 15,000 years during eight eruptive periods that average a repose interval (time between active periods of eruption) of approximately 2,000 years (Kuntz and others, 1986). Dating methods used to determine the ages of the lava flows included Carbon-14 dating of charcoal within the lavas and paleomagnetic correlation of flows (Kuntz and others, 1982).

The eruptive periods of the Great Rift are named "H" through "A," in order of oldest to youngest (Table 4.1). The oldest exposed lava flows of the Great Rift are about 15,000 years old and record the initiation of the COM lava field. More lava flows erupted between approximately 13,000 and 3,600 years ago and mark the continued development of the COM lava field. The youngest lava flows of the Great Rift are approximately 2,500 to 2,000 years old and record the formation of the Kings Bowl and Wapi lava fields and the most recent eruptions of the COM lava field. The Kings Bowl and Wapi lava fields, which formed approximately 2,200 years ago, are located southeast of the COM lava field along the Great Rift (Figure 4.1). For illus-

Eruptive Period	Radiocarbon Age (yr)	Informal Name	Type of Lava Surface	Source vents
A	n.d.	Broken Top	Mostly Pāhoehoe	Eruptive fissures, east and south of Broken Top cinder cone
	2,076 +/- 45	Blue Dragon	Mostly Pāhoehoe	Eruptive fissures south of Big Craters
	2,205 +/- 25	Trench Mortar Flat	Mostly Pāhoehoe	Eruptive fissures between Big Cinder Butte and the Watchman cinder cones
	n.d.	North Crater	Mostly Pāhoehoe	North Crater cinder cone
	2,400 +/- 300	Big Craters (Green Dragon)	Mostly Pāhoehoe	Eruptive fissure at north end of Big Craters
	n.d.	Serrate	Blocky and 'A'ā	North Crater cinder cone (?)
	n.d.	Devils Orchard	Blocky and 'A'ā	North Crater cinder cone (?)
	n.d.	Highway	Blocky and 'A'ā	North Crater cinder cone (?) or vent (?) between Grassy Cone and Sunset Cone
	2,222 +/- 100	Kings Bowl	Mostly Pāhoehoe	Fissure vents north and south of Kings Bowl
	2,270 +/- 50	Wapi	Mostly Pāhoehoe	Vents at Pillar Butte
B	n.d.	Vermillion Chasm	Mostly Pāhoehoe	Eruptive fissures at Vermillion Chasm
C	6,020 +/- 60	Sawtooth	Mostly 'A'ā	Big Cinder Butte cinder cone
	n.d.	South Echo	Mostly Pāhoehoe	Eruptive fissures south of Echo Crater
	n.d.	Sheep Trail Butte	Pāhoehoe and 'A'ā	Sheep Trail Butte cinder cone
	n.d.	Fissure Butte	Pāhoehoe and 'A'ā	Fissure Butte cinder cone
	n.d.	Sentinel	Mostly Pāhoehoe	The Sentinel cinder cone
D	n.d.	Silent Cone	Mostly 'A'ā	Silent Cone cinder cone
	6,600 +/- 60	Carey Kipuka	Mostly 'A'ā	Silent Cone cinder cone (?)
	n.d.	Little Laidlaw Park	Mostly 'A'ā	Silent Cone cinder cone (?)
E	7,360 +/- 60	Grassy Cone	Mostly Pāhoehoe	Grassy Cone cinder cone
	7,470 +/- 80	Laidlaw Lake	Mostly Pāhoehoe	Grassy Cone cinder cone
G	12,010 +/- 150	Sunset	Mostly Pāhoehoe	Sunset Cone cinder cone
	[12000]	Carey	Mostly Pāhoehoe	Sunset Cone cinder cone
H	15,100 +/- 160	Kimama	Mostly Pāhoehoe	unknown**
	n.d.	Little Prairie	Mostly Pāhoehoe	unknown**
	n.d. = not determined			** (Possibly Echo Crater and/or Crescent Butte cinder cones)

Table 4.1. The more prominent lava flows of the Great Rift, specifically those visitors most often encounter while visiting CRMO, within their respective eruptive periods labeled "A" to "H" (from youngest to oldest). Simplified from Kuntz and others, 1986; refer to original publication for a thorough list of all known lava flows of the Great Rift.

trations of the development of the COM, Kings Bowl, and Wapi lava fields throughout the eruptive periods of the Great Rift, see Kuntz and others (1986).

IN DEPTH

<u>The Great Rift: A Hidden Danger that may Erupt Again</u>

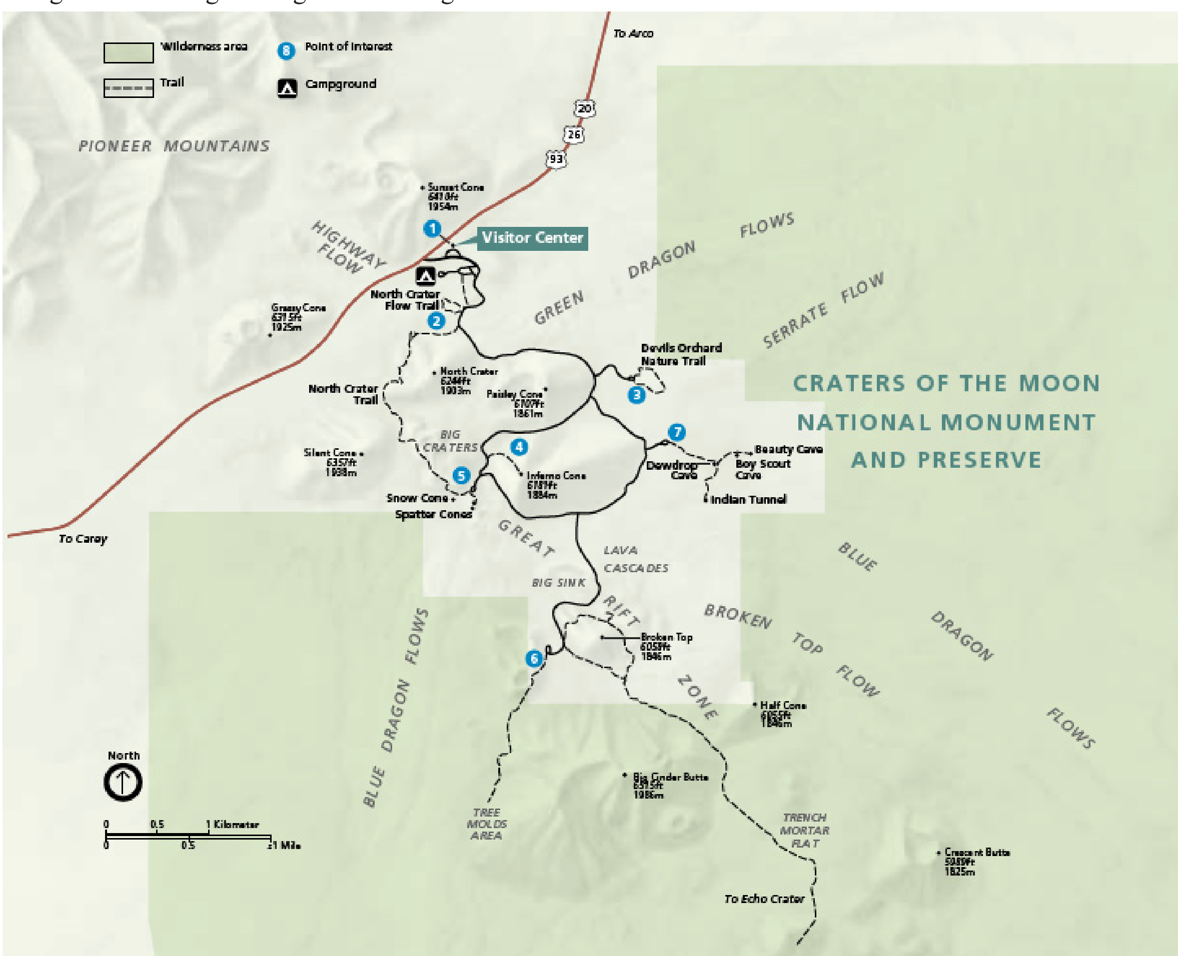
The Great Rift is an active volcanic rift zone that cuts across CRMO. It is located within about 30 km (20 miles) of several communities of southeastern Idaho. The Great Rift has the potential to erupt again in the near future. The shortest length of time that separated eruptive periods of the Great Rift was a few hundred years, and the longest time span about 3,000 years. The average time span that separates the eruptive periods of the Great Rift is about 2,000 years. Relative-age (chronological) dating suggests that the last eruptions of the Great Rift occurred about 2,000 years ago. Absolute age-dating studies using the Car-

The Fifth Principle of Interpretation

"Interpretation should aim to present a whole rather than a part, and must address itself to the whole man rather than any phase."

from: *Interpreting Our Heritage* (1977)
by Freeman Tilden

To apply the Fifth Principle of Interpretation, a program should incorporate universal concepts that are important to all people – for example, the need for shelter, protection of family, sustenance, and safety. Geologic hazards are important topics that the visiting public should be informed of, as they evoke universal concepts that affect the "whole person."



<u>Figure 4.3</u>. Detailed map of the developed portion of Craters of the Moon National Monument and Preserve (map courtesy of CRMO). Hiking trails and points of interest are noted by numbers: 1. CRMO Visitor Center; 2. North Crater Flow and North Crater Trails; 3. Devils Orchard Nature Trail; 4. Inferno Cone Trail; 5. Spatter Cones; 6. Tree Molds, Broken Top, and Wilderness Trails; and 7. Caves Trail. CRMO Wilderness is shown in green.

The Third Principle of Interpretation

"Interpretation is an art, which combines many arts, whether the materials presented are scientific, historical, or architectural. Any art is in some degree teachable."

from: *Interpreting Our Heritage* (1977)
by Freeman Tilden

Tilden's Third Principle of Interpretation can be applied to the use of food as a medium for interpreting seemingly complex scientific topics to the public. Food provides familiar objects that visitors can remember later as metaphors for complicated geologic processes.

Cracks in the Snake River Plain

The North American continent is being pulled apart by continental extension of the Basin and Range Province, forming long mountain ranges separated by valleys. That's why, for example, when you drive east to west across Nevada you cross a mountain range, then a valley, a mountain range, then a valley, several times. You can use a Snickers© bar to demonstrate what this extension does in the flat Snake River Plain, where we don't have mountains anymore, but instead magma erupts at times through giant cracks called rift zones.

To demonstrate, hold a big Snickers© bar and pass out mini-Snickers© bars to some of the visitors so they can also do the demonstration. You can simulate Basin and Range extension by grasping the ends and slowly pulling the bar apart. But the bar doesn't really break apart very easily, does it? You can see that the chocolate top layer cracks apart, but the caramel layer is gooey and doesn't break; rather it tries to come up through the cracks in the chocolate (Figure 4.2). Imagine that the top chocolate layer is the surface of the Earth – the cold, outer crust. It breaks along somewhat straight lines, or big cracks. When this happens, the molten rock underneath (perhaps magma left over from passage over the Yellowstone Hotspot – caramel in the case of the Snickers© bar!) comes up through the cracks and erupts onto the surface.

Figure 4.2. *The outer, chocolate layer of the Snickers© bar can represent the surface of the Earth, while the inner, caramel layer can represent magma underneath the surface. When you pull the Snickers© bar apart, that represents continental extension of the Basin and Range Province as cracks open in the top layer of chocolate. Some of the caramel underneath will come up through the cracks, similar to magma erupting onto the surface through volcanic rift zones. (Photograph by L. Ramacher).*

bon-14 method verify that the last eruption was less than 2,100 years ago (Kuntz and others, 1986). Accordingly, the Great Rift seems to be due for another period of eruptive activity; it could happen in perhaps a few weeks, or a few centuries, from now.

Several communities in southeastern Idaho could be impacted by eruptions along the Great Rift – for example, Carey, Arco, and American Falls. Carey is a town of approximately 500 residents located about 40 km (25 miles) west of the Great Rift, but adjacent to the western boundary of the COM lava field. Similarly, Arco is a town with about 1,000 people located 30 km (18 miles) east of the Great Rift, but only a few kilometers east of the eastern boundary of the COM lava field. American Falls has 4,000 residents, is near the Wapi lava field, and could be affected if a future eruption formed a lava dam that blocked the flow of the nearby Snake River. Depending on the locations of future eruptions, any of these communities could face hazards associated with pyroclastic eruptions or basaltic lava flows. The greatest danger faced by communities close to the Great Rift is that posed by being in the path of effusive lava flows. Depending on their proximity to active vents and wind conditions, other hazards faced by these communities could include exposure to toxic or corrosive volcanic gases. Danger posed by volcanic gases generally decreases with increasing distance from active vents. These communities could also face a danger of fires caused by burning vegetation or structures that come in contact with flowing lava. Explosions can occur if flowing lava encounters bodies of water, such as lakes or rivers (Sigurdsson and others, 2000). Several major highways are located either adjacent to or within the boundaries of the Great Rift – Interstate-86 and Idaho state highway 24 near the Wapi lava field and US 20/26/93 within the COM lava field. Portions of highways may be unusable during and after eruptions.

Staff and facilities at CRMO and the nearby Idaho National Laboratories would also be affected by volcanic events. It is reasonable to expect that another eruption within the Great Rift will happen some time during the next few centuries. Although the possibility of an eruption during our lifetimes may not be great, no comprehensive volcanic hazard assessment or plan has been prepared for CRMO (Owen, 2003). One seismograph station is located in the northern portion of the monument, near Grassy Cone, that could serve as an early warning system for earthquake activity associated with the movement of magma below the surface (NPS Geologic Resources Division, 2001). Researchers from the EarthScope Program believe that the one seismograph located within CRMO may not give enough warning because the signal may be mistaken for noise; they suggest that CRMO needs a small network of long-period seismographs to monitor seismic conditions adequately. Earthscope is expanding the scientific community's knowledge of the structure and tectonic activity of the North American continent and can be investigated at www.earthscope.org.

Being prepared for the dangers associated with volcanic activity is a sound decision for planners in the region. Strategic hazard planning for possible future eruptive activity within the Great Rift by CRMO and the surrounding communities could save lives and reduce property damage.

Craters of the Moon Lava Field

The COM lava field consists of at least 60 separate basaltic lava flows, ranging in age from 15,000 to 2,000 years old. It covers an area of approximately 1,600 km^2 (618 mi^2) and contains approximately 30 km^3 (7 mi^3) of lava flows and pyroclastic deposits (Kuntz and others, 1986). Approximately 25 basaltic cinder cones are located in the COM lava field (Kuntz and others, 1987).

Pāhoehoe and ´a´ā lava flows both occur within the COM lava field. According to Stephens (1988), ropey pāhoehoe lavas flow at temperatures above approximately 1,000 °C (1,800 °F). They tend to leave a ropey, folded surface after cooling. Chunky, jagged ´a´ā lavas flow at lower temperatures down to approximately 925 °C (1,700 °F) and move slower than pāhoehoe. The more-viscous nature of ´a´ā flows causes chunks of solidified lava at the front of the flow to get incorporated back into the main lava flow, producing large blocks of lava that are carried along the frontal edge of the flows. This can be compared to "tire treads" left in mud. The composition of lava flows within the COM lava field range from 44% to 64% silica (SiO_2) and contain relatively high concentrations of elements common to continental crust (Ti, Fe, Na, K, and P) and relatively low concentrations of elements more common to oceanic crust (Mg and Ca) (Hughes and others, 1999; Kuntz and others, 1986; Kuntz and others, 1987; Owen, 2003).

The Big Craters, Trench Mortar Flat, Blue Dragon, Broken Top, North Crater, Orchard-Highway, and Serrate-Devils flows are the youngest flows within the COM lava field and represent most of the lava flows that visitors to the developed portion of CRMO observe and investigate (Figure 4.3) (Kuntz and others, 1986; Kuntz and others, 1987). Several older flows are accessible within CRMO, including the Sawtooth, Grassy Cone, Sunset NW, and Sunset NE flows.

Volcanic Processes in Hawai'i and Iceland show how the CRMO Landscape Developed

Volcanic eruptions occurring in Hawai'i and Iceland are similar to those that have occurred along the Great Rift. Both areas experience basaltic eruptions due to their location either above a hotspot in the interior of an oceanic plate (Hawai'i), or at a hotspot located right along the axis of the Mid-Atlantic Ridge (Iceland). The Great Rift doesn't have large and steep volcanoes like Mt. St. Helens or Mt. Rainier – subduction zone volcanoes that can have large explosive eruptions. But similar to Hawai'i and Iceland, Great Rift magma erupts out of long, narrow fissures (Figure 4.4). The lava can be very fluid when it's still hot. As magma rises in the crack, the drop in pressure causes the gases to expand and come out of solution, producing a "curtain of fire" (Figure 4.5).

Eventually a fissure becomes clogged, and the eruption focuses down to a few or a single vent. The magma erupts higher into the air than if it erupted along the entire fissure. These "fire fountains" can be greater than 300 meters (1,000 feet) high. Imagine holding your finger over a garden hose and seeing the water shoot farther than it did before you covered up part of the opening and caused pressure to build up in the hose. Cinder cones, such as Big Cinder Butte, can form when erupting lava cools off in the air and the solid particles (cinders) pile up on the surface. If winds are blowing at the time, the cinders will be blown to the downwind side of the erupting fissure. Big Cinder Butte has an eruptive fissure on its western side. To visualize the processes, note the fire fountain occurring during the 1973 eruption of Eldfell cone, in Iceland (Figure 4.6), and the similarity of that emerging cinder cone to Big Cinder Butte at CRMO (Figure 4.7).

At the close of an eruption sequence, when a fissure has almost completely clogged up, there may be only a few small areas where the eruption is still taking place. During this "last gasp" of an eruption, blobs of magma erupting out of these small areas cool right around the vent where they accumulate to form spatter cones (which resemble mini-volcanoes) (Figure 4.8). The Blue Dragon lava flow partially erupted from the Spatter Cones on the CRMO Loop Road (Figure 4.9) and is the lava flow that formed the lava tube caves that can be explored on the Caves Trail.

The Fourth Principle of Interpretation

"The chief aim of interpretation is not instruction, but provocation."

from: *Interpreting Our Heritage* (1977)
by Freeman Tilden

The following material applies the Fourth Principle of Interpretation by challenging the visitor to imagine what an actual volcanic eruption at CRMO must have been like. By seeing pictures of recent volcanic eruptions in Iceland and Hawai'i, the visitor is provoked into forming mental pictures and deepening their understanding of how the strange features of a rugged volcanic landscape might have formed.

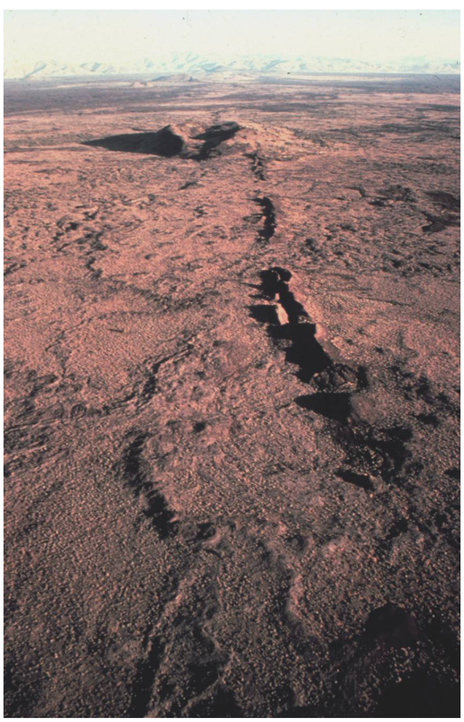


Figure 4.4. Aerial photograph of the Great Rift, looking north-northwest. (Courtesy CRMO).

Figure 4.5. Photograph of a fissure eruption in Hawai'i (Courtesy U. S. Geological Survey (USGS), Hawaiian Volcano Observatory [HVO]).

Figure 4.6. Eldfell cinder cone forming during the 1973 eruption on the island of Heimaey in Iceland. The town of Vestmannaeyjar is in the foreground (Photograph courtesy USGS).

Figure 4.7. CRMO's Big Cinder Butte cinder cone (right), looking southeast from North Crater Trail. The Spatter Cones are in the left foreground. (Photograph by K.E. Truitt).

Figure 4.8. Spatter cone forming during an eruption on Pu'u 'Ō'ō in Hawai'i. Note the lava flowing from the spatter cone (Photograph courtesy USGS, HVO).

Figure 4.9. The Spatter Cones at CRMO, looking southeast from North Crater Trail. The Blue Dragon lava flow partially erupted from the Spatter Cones and surrounds them to the east, south, and west. (Photograph by R.J. Lillie).

IN DEPTH

Crustal Extension and Volcanism in the Northern Great Rift

Many eruptive and non-eruptive fissures can be found that are associated with the Great Rift in the CRMO Wilderness (Figure 4.10). These areas are accessible via a day or multi-day hike along the Wilderness Trail. Field mapping of fissures was conducted in the summer and fall of 2004 in order to produce a more detailed map of the eruptive and non-eruptive fissures of this area than has been previously published (Truitt, 2006). The field mapping area is located in the northern portion of the Great Rift (Figure 4.1).

The mapping project attempted to distinguish between the eruptive and non-eruptive fissures present, and to highlight the lineaments of eruptive spatter that may indicate the presence of concealed eruptive fissures. The main eruptive craters and the cinder cones in the area were also highlighted (Figure 4.11). The map was produced with ArcGIS and shows the geological units (lava flows) overlying Digital Orthophoto Quad (DOQ) images to highlight topography. Eruptive fissures, non-eruptive fissures, and spatter lineaments were mapped using Trimble GeoExplorer3 GPS units and are highlighted along with locations of eruptive craters that were digitized from the DOQ images.

The map of the study area (Figure 4.11) shows that eruptive activity and extension follow the approximately NNW-SSE trend of the Great Rift and other volcanic rift zones of the ESRP. Only one eruptive fissure, along with lineaments of spatter, is apparent between Big Cinder Butte and Crescent Butte. Non-eruptive fissures seem to be absent near the main

Figure 4.10. CRMO Wilderness in the field studies area, looking southeast from the top of Big Cinder Butte. The labeled features are cinder cones. (Photograph by K.E. Truitt).

eruptive fissure in the Trench Mortar Flat (2,200-year old) pāhoehoe flow. This lava flow is partially covered to the northeast by the slightly younger Broken Top pāhoehoe flow that may conceal additional eruptive or non-eruptive fissures. There are more than 100 lava tree molds immediately adjacent to the eruptive fissure, suggesting that the eruption was a single, short-lived, and relatively non-violent eruption.

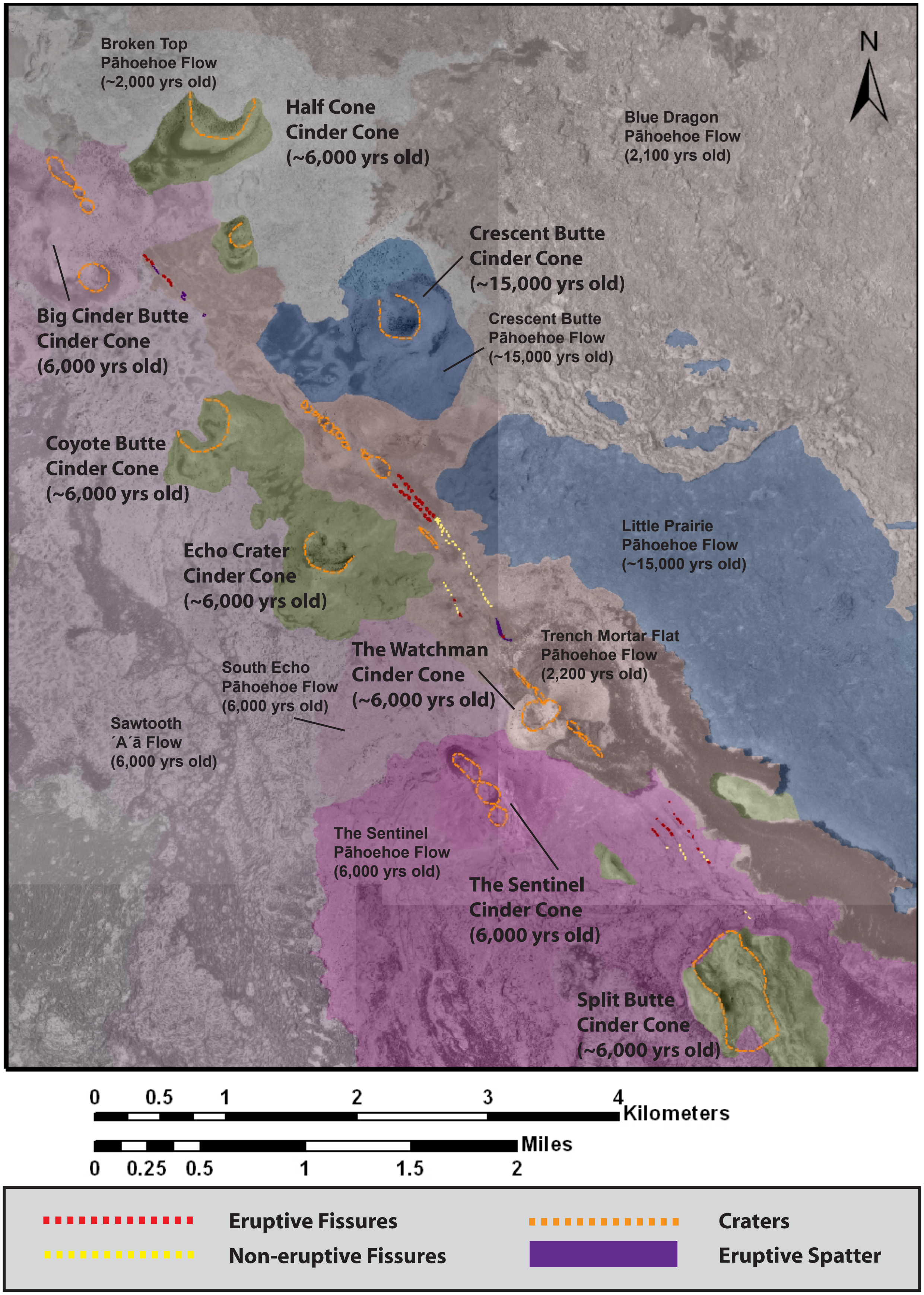
Numerous eruptive features are located between Crescent Butte and The Watchman within the Trench Mortar Flat pāhoehoe flow, including a series of large craters northwest of two main eruptive fissures. Numerous non-eruptive fissures are present in the Trench Mortar Flat lava flow southeast from the eruptive fissures. The eruptive fissures probably indicate at least two different eruptive events that were long-lived and/or violent eruptions, as indicated by the series of eruptive craters to the northwest. The non-eruptive fissures probably represent segments of the basalt dikes where rising magma did not reach the surface, instead cooling at some depth below the surface and leaving open cracks on the surface (M.A. Kuntz, personal communication, 2005).

Three eruptive fissures are shown between The Watchman and Split Butte, within The Sentinel pāhoehoe flow. These fissures probably represent three separate eruptive events that occurred approximately 6,000 years ago. Non-eruptive fissures extend farther southeast and are assumed to also be areas where ascending magma did not quite reach the surface and instead cooled in place. Alternatively, these non-eruptive fissures may be part of a paired set(s) of non-eruptive fissures that flank an eruptive fissure (possibly concealed) (M.A. Kuntz, personal communication, 2007).

The mechanisms of eruptive and non-eruptive fissure formation within the ESRP and the Great Rift may be explained by referring to Hughes and others (1999) and Kuntz and others (2002) (Figure 4.12). Hughes and others (1999) suggest that the rise of basalt dike intrusions probably causes formation of non-eruptive fissures on the surface above the dikes, inferring that formation of non-eruptive fissures probably occurs as the basalt magma is ascending toward the surface through the fissure, but stalls out when neutral bouyancy is reached (when the force of the rising magma is equal to the weight of the overlying materials). Where the basalt dike intrusion does not fully reach the surface and cause an eruption, only a non-eruptive fissure will remain on the surface.

Kuntz and others (2002) propose that formation of non-eruptive fissures occurs at equal distances on both sides of an eruptive fissure, due to tension in the crust as the magma rises within the dike to a critical depth, 750-1000 m (2,500-3,300 ft) based on fissures within the ESRP. Two field-study areas for non-eruptive fissure formation (for this model) are within the southern portion of the Great Rift, Open Crack Rifts and King's Bowl lava field (Figure 4.1). Parallel sets of non-eruptive fissures are found on either side of the eruptive fissure of the Kings Bowl lava field. Open Crack Rifts display two sets of parallel non-eruptive fissures without obvious eruptive fissures between them, suggesting that the ascending magma never reached the surface to cause fissure eruptions; instead cooling in place at some depth beneath the surface. Further studies may eventually reveal the exact nature of non-eruptive fissure formation within the CRMO Wilderness.

Figure 4.11 (next page). Map produced from field studies of the eruptive and non-eruptive fissures, and lineaments of eruptive spatter, found in the northern portion of the Great Rift within the CRMO Wilderness (Truitt, 2006). Eruptive fissures are shown as dashed red lines, non-eruptive fissures as dashed yellow lines, and eruptive craters as dashed orange lines. Lineaments of eruptive spatter that indicate possibly concealed eruptive fissures are shown in dark purple. Age relations between the lava flows, determined by age-dating and field relationships, are from Kuntz and others (1986). The general NNW-SSE trend of extensional features can be seen by the alignment of cinder cones and fissures. The location, within CRMO, of the field studies is shown in Figure 4.1.



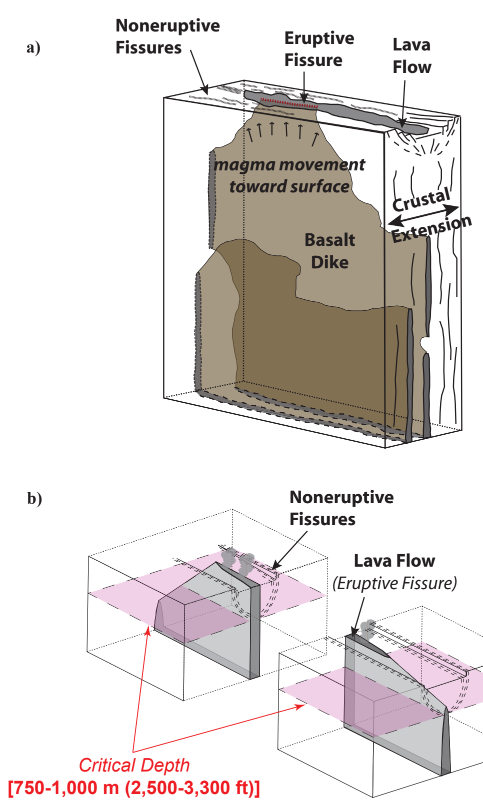
N
Broken Top
Pāhoehoe Flow
(~2,000 yrs old)
Half Cone
Cinder Cone
(~6,000 yrs old)
Blue Dragon
Pāhoehoe Flow
(2,100 yrs old)
Crescent Butte
Cinder Cone
(~15,000 yrs old)
Big Cinder Butte
Cinder Cone
(6,000 yrs old)
Crescent Butte
Pāhoehoe Flow
(~15,000 yrs old)
Coyote Butte
Cinder Cone
(~6,000 yrs old)
Little Prairie
Pāhoehoe Flow
(~15,000 yrs old)
Echo Crater
Cinder Cone
(~6,000 yrs old)
The Watchman
Cinder Cone
(~6,000 yrs old)
Trench Mortar Flat
Pāhoehoe Flow
(2,200 yrs old)
South Echo
Pāhoehoe Flow
(6,000 yrs old)
Sawtooth
´A´ā Flow
(6,000 yrs old)
The Sentinel
Pāhoehoe Flow
(6,000 yrs old)
The Sentinel
Cinder Cone
(6,000 yrs old)
Split Butte
Cinder Cone
(~6,000 yrs old)
0 0.5 1 2 3 4 Kilometers
0 0.25 0.5 1 1.5 2 Miles
Eruptive Fissures
Non-eruptive Fissures
Craters
Eruptive Spatter

IN DEPTH

Dike Propagation and Fissure Eruptions: A summary of processes we can observe and lessons being learned in Iceland and Hawai'i

In Iceland, the Krafla volcanic center has been studied in some detail. Iceland is a place where a hotspot surfaces right along the Mid-Atlantic Ridge. Krafla Volcano is located in northern Iceland along the fissure swarm that may be thought of as the surface expression of the Mid-Atlantic Ridge (Figure 4.13). The Krafla volcanic system has historically been active for many years, then dormant for long periods of time.

The two most recent active periods for Krafla were 1724-1729 and 1975-1984. Rifting episodes at Krafla are typically marked by a sequence of events: 1) continuous intrusion of magma from magma chambers beneath the surface into systems of dikes; 2) periods of increase in elevation of an area interrupted by rapid elevation decrease; and 3) fissure eruptions (Arnadottir and others, 1998). One such rifting episode occurred in 1984. Magma erupted from at least 2 magma chambers, at different depths beneath the surface, from a 1 m (3 ft) wide by 9 km (~6 mi) long dike. At the same time, earthquake activity migrated along fissures away from the magma chamber. Increasing earthquake activity was a signal that magma was being injected laterally outward from the magma chambers into the dikes – activity that produced a fissure eruption (Arnadottir and others, 1998).



Relatively continuous basalt fissure eruptions also occur in Hawai'i. The Big Island called Hawai'i is located directly above an oceanic hotspot. Kīlauea volcano is one of several volcanoes on the island and is currently the most active. The East Rift Zone on Kīlauea is an area of active dike injection that has experienced relatively continuous fissure eruptions since 1983 (Figure 4.14). Earthquake activity and surface deformation occurring just hours before two recent fissure eruptions on the East Rift Zone revealed that magma was moving into dikes in those areas and that fissure eruptions were imminent.

A basaltic dike intrusion resulted in a fissure eruption along the East Rift Zone in January, 1983 (Rubin and others, 1998; Heliker and Mattox, 2003). Earthquake swarms were recorded in the area of Makaopuhi Crater that ultimately extended 16 km (10 mi) eastward along the East Rift Zone. Within 90 minutes of the increase in seismicity, the summit of Kīlauea tilted, showing that magma was moving outward from the magma chamber. This indicated that there was a physical connection, a fluid conduit, connecting the earthquake activity underneath Makaopuhi Crater to the magma chamber underneath Kīlauea.

Within 6 hours of the increase in seismic activity, earthquakes migrated to Nāpau crater, and then seismicity decreased. Tilting was noted 8 km (5 mi) farther eastward on the East Rift Zone at Kalalua. Within 12 hours, a fissure eruption occurred from Nāpau Crater to Kalalua, which eventually reduced to a central vent at Pu'u 'Ō'ō (Rubin and others, 1998; Heliker and Mattox, 2003). This eruption represented the onset of eruptions from Pu'u 'Ō'ō for the next two decades.

In January 1997, a fissure eruption occurred on the East Rift Zone from Pu'u 'Ō'ō to Nāpau Crater. Increased earthquake activity at Nāpau Crater and Kīlauea, as well as tilting at Kīlauea summit, were

Figure 4.12. Models of eruptive and non-eruptive fissure formation within the ESRP and Great Rift. Both models show fissure eruptions (and eruptive fissure formation) on the surface above basalt dikes where magma has risen to the surface. a) Non-eruptive fissure formation at the surface directly above basalt dike intrusions that did not reach the surface and instead cooled in place at some depth below the surface. The eruptive fissure, shown in red, forms where the basalt dike intrusion reaches the surface and causes a fissure eruption. Modified from Hughes and others (1999). b) Non-eruptive fissure formation occurring at the surface at equal distances on either side of the location of an eruptive fissure, due to stresses in the crust radiating outward from the rising basalt dike intrusion [starting at a critical depth of 750-1000 m (2,500-3,300 ft)]. This model is based on studies in the southern portion of the Great Rift at the Open Crack Rifts and Kings Bowl lava field (shown in Figure 4.1). Modified from Kuntz and others (2002).

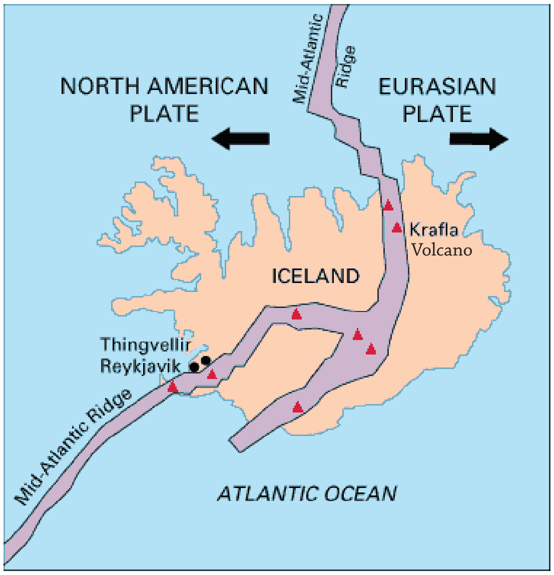


Figure 4.13. Krafla Volcano is located in northeastern Iceland, along with other active volcanoes, within a zone of extension that is the surface expression of the Mid-Atlantic Ridge. The Mid-Atlantic Ridge is shown in purple. Active volcanoes in Iceland are shown as red triangles (Illustration courtesy USGS).

recorded 8 hours before the fissure eruption occurred (Owen and others, 2000). Both eruptions revealed that increased earthquake activity and tilting of the summit above the magma chamber were precursory warnings that magma was moving through dikes upward to the surface.

The movement of basalt magma from magma chambers through dikes beneath the surface of the Earth can produce destructive fissure eruptions when the magma reaches the surface. This process is difficult to predict, however, as it cannot be directly observed. Recent eruptions in Iceland and Hawai'i have revealed processes that can indirectly inform scientists that magma is moving from a magma chamber through dikes and that a fissure eruption may be imminent. With continued monitoring of eruptions in these two active volcanic zones, more information may be revealed about the process of dike propagation and how fast it typically occurs. Learning more about how magma moves through dikes to the surface could contribute to better volcanic hazard mitigation in areas of active volcanism worldwide, including areas without sophisticated monitoring systems like the Great Rift at CRMO.

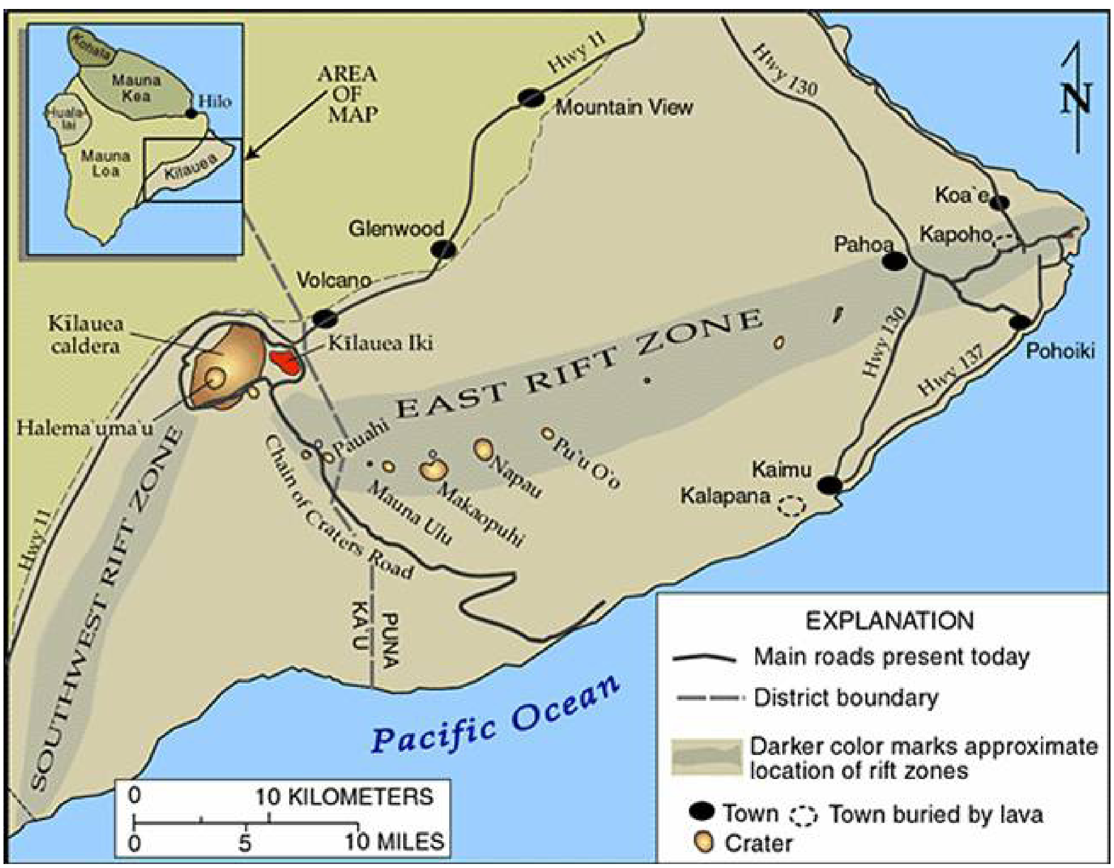


Figure 4.14. The East Rift Zone of Kīlauea Volcano, on the Big Island of Hawai'i, includes several craters – Pauahi, Mauna Ulu, Makaopuhi, Nāpau, and Pu'u 'Ō'ō. Nearby towns are shown as solid black circles and Kalapana, a town buried by recent lava flows, is shown as a black dashed circle. Kīlauea Caldera is shown in center left. (Map courtesy USGS, HVO).

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